REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1998	Final, July to December 1997

4. TITLE AND SUBTITLE

Limited Handling Qualities Evaluation of Longitudinal Flight Control Systems Designed Using Multiobjective Control Design Techniques (HAVE INFINITY II)

5. FUNDING NUMBERS

JON: M96J0200

PEC:

6. AUTHOR(S)

John R. Anderson, Captain, USAF
Eric A. Boe, Captain, USAF
Maurizio Cantiello, Captain, ItAF
Mark S. Spillman, Captain, USAF
Michael J. Stephens, Captain, USAF
Jonathan R. Stevenson, Lieutenant, USN

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES

USAF TPS/EDA
220 S. Wolfe Ave.
Edwards AFB CA 93524-6020

8. PERFORMING ORGANIZATION REPORT NUMBER

AFFTC-TR-97-48

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFIT/Dept. of Aeronautical Engineering
Bldg 642, 2nd Floor
2950 P Street
Wright-Patterson AFB OH 45433

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

N/A

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

13. ABSTRACT *(Maximum 200 words)*

This report presents the flight test results of the Project HAVE INFINITY II limited flight test. The objective of this limited flight test was to evaluate the six HAVE INFINITY II longitudinal flight control designs in support of an Air Force Institute of Technology (AFIT) Master's degree thesis. The thesis investigates the practicality of using modern multiobjective techniques for flight control system design. During the test program, 12 evaluation sorties, totaling 14.2 flight hours, were flown in a Calspan Variable Stability System (VSS) Learjet. Tests were conducted by the USAF Test Pilot School, Edwards AFB, California, from 29 September through 10 October 1997, at the request of the AFIT, Wright-Patterson AFB, Ohio.

14. SUBJECT TERMS

handling qualities	flight control systems	VSS II Learjet
variable stability	optimal control theory	H2 optimization
landing tasks	state-space optimization techniques	H-Infinity optimization theory

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

PREFACE

This technical report presents the results of a limited handling qualities evaluation of longitudinal flight control systems designed using multiobjective, control design techniques (HAVE INFINITY II). This limited flight test evaluated six HAVE INFINITY II longitudinal flight control designs during the approach and landing phase of flight in support of an Air Force Institute of Technology (AFIT) Master's degree thesis. This thesis investigated the practicality of using modern, multiobjective model-following techniques for flight control system design. Five of the HAVE INFINITY II longitudinal flight control systems were implemented using modern, multiobjective model-following design techniques, and the sixth used classical design techniques.

Testing was conducted at the Air Force Flight Test Center, Edwards AFB, California, with the evaluation landings being performed at the Palmdale Airport, Palmdale, California, Runway 25, from 1 through 9 October 1997. The USAF Test Pilot School (TPS), Edwards AFB, California, was the responsible test organization. The testing was requested by AFIT, Wright-Patterson AFB, Ohio, and was conducted under the authority of the Commandant, USAF TPS.

The HAVE INFINITY II test team would like to thank Mr. Russ Easter and Mr. Scott Buethe of Calspan Corporation. Their dedicated efforts, through all stages of the test, greatly contributed to the successful outcome of this test program.

This page intentionally left blank.

EXECUTIVE SUMMARY

This HAVE INFINITY II limited flight test was conducted to evaluate the handling qualities of noise sensitivity minimization (H2), mixed H2/output energy minimization (H-Infinity), and classical longitudinal flight control system designs during the approach and landing phase of flight in support of an Air Force Institute of Technology (AFIT) Master's thesis. This thesis investigated the practicality of using modern, multiobjective model-following techniques for flight control system design. The H2 optimal control design methods sought to automatically reject noise, and the H-Infinity optimal methods sought to minimize the output errors. The first test objective was to evaluate the longitudinal handling qualities of H2, mixed H2/H-Infinity, and classical longitudinal flight control configurations. The second test objective was to collect pilot comments on the longitudinal handling qualities of the flight control configuration after mainwheel touchdown. Five of the HAVE INFINITY II longitudinal flight control systems (FCSs) were implemented using state-space, multiobjective model-following design techniques, and the sixth used classical design techniques.

Tests were conducted by the USAF Test Pilot School (TPS), Edwards AFB, California, from 1 through 9 October 1997. The tests were conducted at the Air Force Flight Test Center, Edwards AFB, California, and the evaluation landings occurred at Palmdale Airport, Palmdale, California, Runway 25. Six T-38 practice sorties were flown to standardize and practice the landing tasks. Twelve evaluation sorties, totaling 14.2 flight hours, were accomplished in the Calspan Variable Stability System (VSS) Learjet. Three of these evaluation sorties included a C-23 target aircraft for up-and-away evaluation of pilot-in-the-loop oscillation tendencies of the HAVE INFINITY II control laws. The testing was requested by AFIT, Wright-Patterson AFB, Ohio, and was conducted under the authority of the Commandant, USAF TPS. Testing was conducted under USAF TPS Job Order Number M96J0200.

All objectives were met. Model verification, validation, and subsequent flight testing allowed for a satisfactory evaluation of the handling qualities of the HAVE INFINITY II FCS designs. The HAVE INFINITY II flight control laws were correctly implemented and flown on the Calspan VSS Learjet. The tool used in achieving this was the use of ground and in-flight verification and validation simulation of the HAVE INFINITY II flight control laws tested. The Calspan Learjet simulation results were very similar on the ground and in the air. This was confirmed by the correlation of the ground and flight test time response matches and pilot comments. Details are discussed in the Model Verification and Validation Results section of this report. Handling qualities results indicated that the optimal design methods used gave Level II or better handling qualities with no PIO observed for any of the designs. Most of the Level II comments related to the instability in the H2INI, H2AIN, and H2AOA designs, were caused by the phugoid mode that was unaccounted for in the design process (Table 1). These designs may have been rated closer to Level I if the phugoid had been included in the design aircraft model.

Proper verification and validation of all models used in the design process is critical. It is paramount that the Responsible Test Organization (RTO) require and support these efforts. The earlier this can be accomplished prior to flight test, the more flexibility the RTO has to implement required changes and avoid the 'fly-fix-fly' approach.

This page intentionally left blank.

TABLE OF CONTENTS

MULTIMEDIA ADJUNCT

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

INTRODUCTION

GENERAL

This report presents the evaluation procedures, concepts, rationale, and results for the limited handling qualities evaluation of longitudinal flight contr ol configurations designed using modern, multiobjective control design techniques. The purpose of the HAVE INFINITY II limited flight test was to evaluate the handling qualities of noise sensitivity minimization (H2), mixed H2/output energy minimization (H-Infinity), and classical longitudinal flight control system designs during the approach and landing phase of flight in support of an Air Force Institute of Technology (AFIT) Master's thesis (Reference 1). The H2 optimal control design methods sought to automatically reject noise (e.g., turbulence) by minimizing the output error signal of a system response given a command and one or several noise inputs. The H-Infinity optimal methods sought
to minimize the output errors of the unknown, but bounded energy inputs. These inputs can be characterized by putting a bound on how tightly the system must track the command or adding an output sensitivity constraint to improve stability margins. While there are many other types of constraints, the two mentioned were successfully used in the analytical phase of this research. Finally, the mixed H2/H-Infinity method optimally tradeoff the different benefits offered by the separate H2 and H-Infinity methods. The output of this method should yield a control law that has better overall tracking and stability characteristics in addition to retaining a capability to reject turbulence. This thesis investigated the practicality of using modern, multiobjective techniques for flight control system (FCS) design.

Twelve sorties, totaling 14.2 hours of flight test, were flown in a Calspan Variable Stability System (VSS) Learjet. Three of the sorties used the C-23 as a target aircraft for a handling qualities during tracking (HQDT) evaluation. The other nine sorties were used exclusively to evaluate landing performance. Six T-38 support sorties were flown prior to the test period. These sorties consisted of practice approaches flown to familiarize and standardize project pilots with the landing tasks performed during the flight test. One 3-hour verification ground test was accomplished on 1 October 1997, to ensure HAVE INFINITY II flight control laws were properly implemented. Validation testing was conducted on the first test sortie to evaluate the response of the flight control laws and the overall closed-loop system response. Testing was conducted at Edwards AFB, California, and the evaluation landings occurred at Palmdale Airport, Palmdale, California, Runway 25 from 1 to 9 October 1997. Testing was requested by AFIT, Wright-Patterson AFB, Ohio, and was conducted under the authority of the Commandant, USAF Test Pilot School (TPS). Testing was conducted under USAF TPS Job Order Number M96J0200.

BACKGROUND

Classical root-locus techniques have traditionally been used to design and refine highly augmented FCS. However, such techniques become cumbersome to use on systems with more than one input or output. Several iterations of the FCS are normally required to optimize the design. State-space, multiobjective design techniques can quickly and efficiently implement and refine highly augmented FCS, once the constraints and performance objectives are known. The H2 and H-Infinity described previously are two multiobjective, state-space techniques that have been postulated for use in designing FCS.

HAVE INFINITY I limited flight test evaluated four flight control designs: one classical, one H2, one H-Infinity, and one mixed H2/H-Infinity configuration. The classical controller was rated Level II on the Cooper-Harper (C-H) Rating Scale (Figure B4, Reference 2), and the H2, H-Infinity, and mixed H2/H-Infinity designs all received Level III C-H ratings. The H2, H-Infinity, and mixed H2/H-Infinity designs contained high frequency and unstable modes internal to the control laws. Model verification and validation testing revealed that predicted time and frequency responses did not match the actual time and frequency responses. Additionally, the Learjet exhibited an uncommanded pitchup in the landing flare, which significantly degraded handling qualities ratings. The HAVE INFINITY I test team felt that the dubious nature of the implementation and the potential negative impact on handling qualities rendered the results inconclusive as to the potential benefits of the multiobjective design techniques used.

Due to the HAVE INFINITY I test results, AFIT made the decision to continue the

multiobjective flight control research in hopes of producing a definitive answer about their utility with regard to handling qualities rather than testing some of the potential advantages of the methods such as turbulence rejection and stability robustness. The AFIT felt that getting good handling qualities using the optimal methods had to be accomplished before more advanced testing could take place. As a result, this test program evaluated several H2 and mixed H2/H-Infinity designs. These designs used a model-following approach. The idea behind model-following is that an ideal closed-loop aircraft model with the desired handling qualities response characteristics is placed in another loop of the command path, in addition to the usual actuator and design aircraft model. The output signal from the ideal closed-loop aircraft model is then differenced with the output signal from the actuator and design aircraft model loop. By minimizing the magnitude of this error signal (which can be done by both the H2 and H-Infinity methods), the output response of the closed-loop (control law plus aircraft) will match the ideal closed-loop aircraft model. The HAVE INFINITY I limited flight test did not use this approach. A classical root-locus design was also tested to provide a baseline comparison with the multiobjective designs. The 6 designs selected for flight test were the best of over 20 initial designs in the areas of command tracking, noise rejection, stability margins, and handling qualities predictions. Handling qualities predictions were made using Hoh's Bandwidth Criteria, landing phase (Reference 2).

The specific breakdown of design and command type for the initial six designs tested and the notation used in discussing each specific design is listed in Table 1.

Unlike the HAVE INFINITY I designs, the HAVE INFINITY II flight control designs did not contain any unstable modes. This allowed them to be implemented in transfer function format. Additionally, the HAVE INFINITY II test team had the opportunity to travel to Calspan Corporation in Buffalo, New York, from 3 to 5 August 1997, for the purpose of performing initial verification and validation testing on the six HAVE INFINITY II flight control designs. This testing was repeated at Edwards AFB 1 day prior to the flight test. Results of this testing were used to verify correct implementation of the HAVE INFINITY II flight control designs. This verification was accomplished by comparing desktop transfer functions with simulation transfer functions to ensure the poles and zeros matched (Appendix C).

Table 1
HAVE INFINITY II FLIGHT CONTROL CONFIGURATION NOTATION

Notation	Design/Command Type
CLASSIC	Root-Locus Design - Angle of Attack (AOA) and Pitch Rate Feedback
H2INI	H2 Optimal - Pitch Rate Command
H2AIN	H2 Optimal - AOA Command through filtering H2INI command input
H2AOA	H2 Optimal - AOA Command
MXINI	Mixed H2/H-Infinity Optimal - Pitch Rate Command
MXAOA	Mixed H2/H-Infinity Optimal - AOA Command

TEST ITEM DESCRIPTION

The HAVE INFINITY II limited flight test consisted of six different longitudinal flight control configurations that were designed using different techniques. These flight control configurations were implemented in the Calspan Learjet FCS. Five of the configurations were designed using multiobjective, state-space analysis: H2, H-Infinity with both sensitivity and complimentary sensitivity weighting, and a mixed H2/H-Infinity design that compromised the benefits of both design techniques optimally. The sixth configuration used classical root-locus design techniques for a baseline comparison with multiobjective designs. The Hoh's Bandwidth Criteria, landing phase, predicted Level I handling qualities for each design (Reference 2). The R. Smith Criteria predicted marginal Level I handling qualities and no pilot-in-the-loop oscillations (PIO) for each design (Reference 4). The six flight control configurations were implemented and flown on the Calspan VSS Learjet.

The HAVE INIFINITY II testbed was the Calspan VSS Learjet, tail number N101VS. The VSS aircraft was a highly modified Learjet Model 24 that functioned as a three-axis, in-flight simulator. The control yoke in the left seat, for the safety pilot, operated the Learjet's conventional FCS. In the right seat, the evaluation pilot had a control stick with a fly-by-wire, response feedback system. The variable stability system included a variable feel system, digital configuration control system, disengage safety logic, control system simulation computer, aircraft motion sensors, and data recording and playback capability. The evaluation pilot's pitch-trim button directly moved the horizontal stabilizer and was not implemented through the VSS control system. In addition, an 8-mm video recording camera was installed with a view over the evaluation pilot's right shoulder for postflight review. This videocamera recorded all cockpit audio, including intercom and radio communication. A detailed description of the VSS aircraft is contained in Appendix A.

TEST OBJECTIVES

The overall objective of the HAVE INFINITY II limited flight test was to evaluate the handling qualities of H2, mixed H2/H-Infinity, and classical longitudinal FCS designs during the approach and landing phase of flight in support of an AFIT Master's thesis (Reference 1). The first specific test objective was to evaluate the longitudinal handling qualities of H2, mixed H2/H-Infinity, and classical longitudinal flight control configurations. The second specific test objective was to collect pilot comments on the longitudinal handling qualities of the flight control configuration after mainwheel touchdown. All the objectives were met.

This page intentionally left blank.

TEST AND EVALUATION

GENERAL

The HAVE INFINITY II limited flight test program was conducted from 1 to 9 October 1997, at Edwards AFB, California, and Palmdale Airport, Palmdale, California, Runway 25. This test program consisted of 12 flights totaling 14.2 hours of flight test. Three evaluation pilots evaluated six different longitudinal FCSs. The initial flight for each evaluation pilot was conducted with a C-23 target aircraft for an HQDT evaluation of each FCS. The FCSs meeting the requirements of the HQDT evaluation were evaluated in the approach and landing phase at Palmdale Airport using a straight-in landing task and a horizontal offset landing task. The evaluation pilots rated the FCS designs using the C-H and PIO rating scales (Figures B4 and B5). Prior to the test flights, the landing tasks were practiced by the evaluation pilots in the T-38 aircraft.

METHODS AND CONDITIONS

Model verification was performed during the ground test phase in the frequency domain to ensure that the HAVE INFINITY II flight control laws and aircraft model were implemented properly. The FCS and aircraft model were verified by checking the poles and zeros of the transfer functions programmed in the VSS Learjet flight control computer with the design state-space model poles and zeros to make sure they matched. Programmed test input (PTI) pulses were then performed with the HAVE INFINITY II flight control configurations implemented for ground simulation to evaluate the closed-loop time response in pitch rate (q) and angle of attack (AOA), as compared to the same closed-loop time responses for the design model. Model validation analysis was performed during the flight test phase to evaluate how well the HAVE INFINITY II flight control laws and aircraft model were simulated in flight. Using PTI pulses, aircraft and desktop time histories of control commands were compared to validate the flight control laws. The PTI pulse time histories were used to compare the overall closed-loop system response.

TEST PROCEDURES

General:

Ground testing was accomplished on every flight control configuration prior to in-flight evaluation. Ground testing provided a means of verifying software implementation for each design configuration on the VSS Learjet.

Model validation data of the aircraft design model and each flight control configuration were collected at 140 KIAS with the aircraft configured as in the landing task (landing gear down and flaps 20 percent). Using PTI pulses, at least three pitch doublets were performed for each configuration.

Prior to advancing to the landing task, each evaluation pilot accomplished Phase II HQDT testing on every flight control configuration, in both 1,000-foot trail and close formation. The HQDT evaluations were accomplished at 140 KIAS and at a minimum altitude of 5,000 feet AGL. This Phase II testing used a C-23 airborne target aircraft. Each flight control configuration was evaluated using a buildup approach starting with low-bandwidth tracking, from a position 1,000 feet in trail of the target, and progressing to high-bandwidth tracking (e.g., HQDT). During both low- and high-bandwidth tracking, the evaluation pilot attempted to change the desired aim point by 10 milliradians. If the flight control configuration did not receive a PIO rating of 5 or 6, close formation was performed. Close formation was accomplished on a 30-degree line with 10-foot wingtip clearance, and nose-tail separation with the C-23 target aircraft. In close formation, the evaluation pilot began with low-bandwidth tracking and proceeded to HQDT testing in a buildup fashion. During close formation HQDT maneuvers, the evaluation pilot attempted to correct the aircraft to a desired position from 10 feet below the desired position. A separate PIO rating was given for the trail position and for the close formation position, if accomplished. Any flight control configuration receiving a PIO rating of 5 or 6 in either tracking task from any pilot was not evaluated in the landing task.

On each flight, the evaluation pilot performed a minimum of one approach and landing with the VSS configured as the baseline Learjet prior to flight testing the HAVE INFINITY II control designs. The test conductor configured the Learjet FCS with the required configuration parameters, and the safety pilot engaged the VSS. The evaluation pilot took control of the aircraft on downwind for the pattern and landing. The safety pilot took control of the aircraft upon the evaluation pilot's determination that a full-stop landing could be accomplished from the current landing. The safety pilot would then take control for the remainder of the ground roll, takeoff, and the climb-to-pattern altitude. The evaluation pilot provided comments on atmospheric conditions affecting the approach.

<u>Straight-In Landing Task</u>:

This task consisted of a 3-degree glide path, using the ILS glideslope to assist with glidepath determination, until the decision height of 200 feet AGL. A visual transition to a consistent flare and touchdown in the desired zone of the landing area was then accomplished. The approach airspeed was between 125 and 135 KIAS, depending on the aircraft weight. The desired touchdown zone was in the desired box described in Figure 1. The target airspeed at touchdown was 10 knots less than approach speed. Airspeed tolerances were +10/-5 knots of the target airspeed. For quality of data, only landings within this touchdown airspeed window were evaluated. A ground test team, in radio contact with the aircrew, verified if the actual touchdown point was inside the desired or adequate touchdown box. The evaluation pilot provided qualitative comments and C-H and PIO ratings (Appendix D) for the approach to mainwheel touchdown in accordance with rating scales (Figures B4 and B5). After mainwheel touchdown, the evaluation pilot provided qualitative comments through nosewheel touchdown to a point (determined by the evaluation pilot) that a full-stop landing could be completed. In accordance with Figure 2, if the straight-in landing did not receive a C-H rating of 8, 9, or 10, this flight control configuration would be evaluated with the horizontal offset landing.

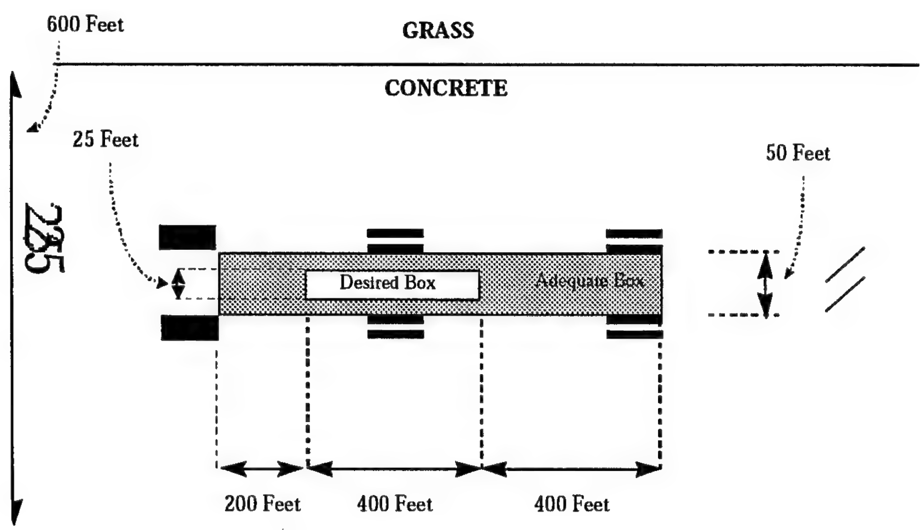

Figure 1 Touchdown Zone

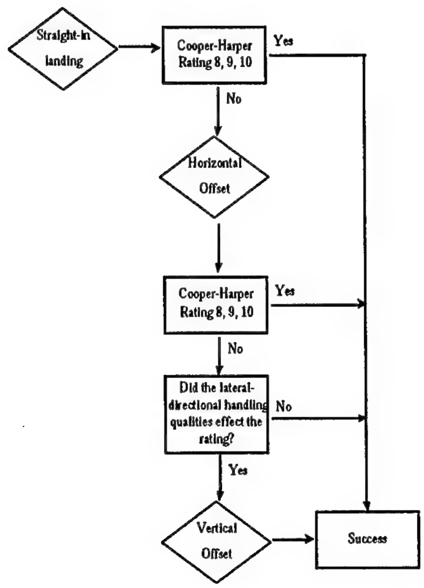

Figure 2 Landing Task Decision Tree

Horizontal Offset Landing Task:

This task forced the pilot to raise the gains by concentrating on both longitudinal and lateral control inputs. The horizontal offset landing task was accomplished by flying a visual pattern with a lateral offset of 300 feet to the right of the runway centerline. At 200 feet AGL, the evaluation pilot would aggressively correct to the centerline. The correction used an initial bank angle between 30 and 45 degrees within 3 seconds, and the initial aggressive lateral corrections were completed by 100 feet AGL. A simultaneous correction was made to intercept a visual glidepath to touchdown. The desired touchdown point was located at the center of the desired zone. Again, the target airspeed at touchdown was 10 knots less than approach speed with the same tolerances as in the straight-in task; only landings within this touchdown airspeed window were evaluated. Pilot comments expected, and rating scales used, were identical to the straight-in landing. In accordance with Figure 2, if the horizontal offset landing did not received a C-H rating of 8, 9, or 10 and the lateral-directional handling qualities affected the C-H rating, this flight control configuration would be evaluated with a vertical offset landing.

Vertical Offset Landing Task:

This task was designed to minimize any lateral-directional handling qualities effects and focus attention completely on the longitudinal axis. The vertical offset landing was accomplished by flying straight and level at the published minimum descent altitude of 397 feet AGL, as if flying a localizer approach. At glideslope intercept, the pilot would aggressively correct to a 3-degree glidepath no later than 100 feet AGL. Pilot comments expected, and ratings scales used, were identical to those discussed for the straight-in landing task. Only landings within the touchdown airspeed window would be evaluated.

A landing could be repeated at the discretion of the test conductor, based on improper setup, extenuating atmospheric conditions, or any factor where a biased rating may have occurred. Test conditions such as minor turbulence or wind variations were documented, but not repeated.

Vertical offset landing tasks were not performed during this flight test because the lateral-directional handling qualities did not effect the pilot ratings.

TEST RESULTS AND ANALYSES

All objectives were met. Model verification and validation and subsequent flight testing allowed for a satisfactory evaluation of the handling qualities of the HAVE INFINITY II FCS designs.

Model Verification and Validation (Frequency and Time Domain):

Model verification was accomplished to ensure the FCSs were correctly coded in the Calspan VSS computer. Since the Calspan VSS Learjet had to simulate an F-16 aircraft, the F-16 design model also had to be properly coded in the VSS computer. The expected open-loop pole and zero locations from the design and the actual open-loop pole and zero locations coded in the VSS computer are shown in Tables C1 through C7. All of the poles and zeros matched well, except those associated with the MXINI controller (Table C7). A simple fix to the computer code of the MXINI controller was attempted at the end of the ground simulation period at Edwards AFB. However, complete verification of the fix was not made prior to the first HQDT sortie due to time constraints. The configuration was spot checked during this flight and dropped from subsequent evaluation, due to the poor resulting flying qualities.

Validation testing was accomplished during ground test by comparing the closed-loop time responses to a PTI pulse at the control stick. The comparison was made between each control system coded on the VSS computer to those generated in the design process. Since the design model was a short period approximation of the F-16 aircraft, only the pitch rate and the AOA responses were examined. The linear time history response comparisons had some discrepancies, but were considered an acceptable validation of the closed-loop response. Figures C1 through C5 illustrate ground time history validation plots.

In addition to comparing PTI pulse time responses for validation, the test team pilots were able to fly simulated approaches with each flight control configuration using an integrated synthetic horizon, attitude direction indicator, and flightpath marker display. This not only gave the pilots a feel for how each control configuration might fly, but provided valuable qualitative validation information that was not obtained from the time response matches. The pilots noticed an apparent negative speed stability behavior in the aircraft for the H2INI, H2AIN, and H2AOA configurations which had not been noticed previously (see Table 1). Upon discussion with Calspan, it was explained that the VSS computer modified the Learjet's short period dynamics to look like F-16 short period dynamics (Figure C6), but did not eliminate or modify the Learjet phugoid. Consequently, when the Learjet phugoid mode was included in the simulation, which had not been done previously, three of the configurations appeared to have negative speed stability. The Learjet phugoid mode was not considered in the design process, upon the advice of the AFIT faculty and Calspan. They felt this mode would not have a significant effect on handling qualities and would add unnecessary complexity and increased order to the resulting flight control designs. In actuality, it appeared that leaving the Learjet phugoid mode out of the design process might have an impact on the handling qualities of the flight control designs. The CLASSIC and MXAOA control configurations did not exhibit any negative speed stability characteristics during piloted ground simulations. The CLASSIC control configuration may have handled the additional dynamics well because it only involved a small amount of gain on the AOA and pitch rate feedback paths. Unlike all of the other flight control configurations, there were no controller dynamics interacting with the phugoid mode in the CLASSIC configuration. The MXAOA controller was dynamic (i.e., a transfer function); however, it was also designed to handle model uncertainty. Thus, the MXAOA control configuration also performed as expected.

In-flight model validation results closely matched the ground model validation results (Figures C7 through C11) and were considered acceptable. The pilots again noticed the apparent negative speed stability characteristic in the H2INI, H2AIN, and H2AOA configurations. Some of the discrepancies in the latter portions of the time histories for the H2INI, H2AIN, and H2AOA configurations were attributed to the apparent negative speed stability. Again, the MXAOA and CLASSIC configurations performed as expected with no apparent instabilities.

Postflight analysis using the design controller and aircraft dynamics revealed that the H2INI, H2AIN, and H2AOA closed-loop configurations contained a slightly unstable first order mode when the Learjet phugoid was included in the aircraft dynamics (Tables C8 through C12).

Ultimately, the verification and validation phase of the test program confirmed the flight control laws implemented and flown were the same as those designed, except for the MXINI configuration. The dynamics of the actual aircraft were different than the dynamics of the design model, due to the exclusion of the phugoid mode from the design model. Thus, the handling qualities ratings reflected the performance of each flight control configuration implemented on an aircraft that differed from the design model. As a result, the H2INI, H2AIN, and H2AOA control configurations were negatively impacted due to a lack of robustness to differences between the design model and the actual aircraft. The system should have been tested with the phugoid mode early in the design process. Then, if a stability problem was found, a redesign could have been accomplished by adding additional uncertainty to the short period model or simply including the phugoid mode in the design. **Early FCS ground tests should be conducted with the highest fidelity aircraft model available to allow time for required redesigns prior to flight test. (R1)**[1]

Handling Qualities Evaluation:

CLASSIC.

The evaluation pilots performed four straight-in and four horizontal offset landings with the CLASSIC flight control configuration. Figures D1 through D4 illustrate the C-H and PIO histograms. Level I C-H ratings were given for each landing with one exception that received C-H 4. All Level I ratings were associated with PIO 1, and the C-H 4 received a PIO 3. All the C-H and PIO ratings were unaffected by differences in wind conditions (Appendix E).

All pilots agreed that the CLASSIC flight control configuration provided a predictable linear initial response, although, the response was somewhat slower than several of the other configurations. The majority of Level I ratings confirmed the satisfactory handling qualities of this configuration; however, while performing HQDT evaluations, pilot two noted that the aircraft response was not linear with respect to the size of the input. If the aircraft response was truly linear, a larger input should result in a larger output over the same period of time. In other words, a faster initial response should occur with a larger input. Pilot two found that large stick inputs did not produce a faster pitch rate response than smaller inputs. While pilot two saw this problem consistently during the HQDT tasks, it was not noticed during any of the landing tasks. On one landing, however, pilot three downgraded the configuration to C-H 4 because desired performance had to be sacrificed when an unexpected pitch response in the flare was encountered. Postflight analysis showed that pilot three increased the size and rate of stick inputs at the initiation of the flare, but the aircraft did not respond faster to these inputs. This forced pilot three to lower gains and accept a long landing. Comments about the pitch response from pilots two and three were consistent with a rate limitation problem in the FCS; however, flight data evaluation did not support a rate limitation problem. No other explanation for the nonlinear pitch response was found. Inputs large enough to uncover the nonlinear pitch response were not required on a majority of the landings, so the problem had little impact on the C-H and PIO ratings. Overall, the CLASSIC flight control configuration was rated Level I.

H2AOA.

The evaluation pilots performed four straight-in and four horizontal offset landings with the H2AOA flight control configuration. Figures D5 through D8 illustrate the C-H and PIO histograms. The H2AOA flight control configuration received the worst ratings of all the configurations flown in the landing tasks. Level II C-H ratings were given for all landings with one exception that received C-H 3. Two landings were given C-H 6 ratings with PIO 4. Another landing was given a C-H 6 rating with a PIO 3. In general, the ratings for the horizontal offset landing task were better than the ratings for the straight-in landing task, although one of the

[1] Numerals preceded by an R within parentheses at the end of a paragraph correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

C-H 6 ratings was given for a horizontal offset task. The ratings of this configuration also worsened with higher winds. The only Level I rating (C-H 3) was given during very light winds (Appendix E).

All three pilots agreed the long-term pitch axis response was slowly divergent. A deviation in airspeed started a pitching moment, resulting in slowly increasing stick forces that continued to buildup in the initial direction until the pilot retrimmed the aircraft. The pitching moment was opposite of what was expected. When the airspeed slowed from a trimmed condition, forward stick pressure was required to keep the nose from rising. The amount of disturbance required to start a divergence was very small. A 1-knot deviation in airspeed was enough to initiate the slow buildup of stick force. The small size of the disturbance, required to initiate the divergence, made the direction unpredictable to the pilot; such that the pilot had no indication whether the divergence would result in a slow buildup of push or pull force. One pilot commented that flying the configuration "felt like trying to balance on a bowling ball." This problem increased pilot workload because the pilots had to pay constant attention to airspeed and pitch attitude, as well as continually retrim the aircraft. These characteristics became less apparent during the offset landing tasks when the pilots were exercising tighter control of the aircraft. Under tight control, the aircraft was not allowed to diverge from trim, and the C-H and PIO ratings improved. Regardless of task, all pilots felt the nose pitch down after mainwheel touchdown. The pilots were unable to keep the nose from dropping with a reasonable amount of stick force and did not attempt to use large displacements of aft stick to arrest the nose movement. Pilot two felt the stick forces increase dramatically in the flare on both a straight-in task and a horizontal offset task, which made the pitch attitude very hard to control. This characteristic generated the two PIO 4 ratings given by pilot two. The small amplitude pitch oscillations caused pilot two to freeze the stick; desired performance was achieved only because the PIO occurred very late in the flare. Overall, the long-term divergent response of this FCS had a large impact on the majority of the landings. The H2AOA flight control configuration was rated Level II.

The divergent nature of the H2AOA flight control configuration was not completely unexpected. As discussed in the Model Validation section of this report, ground simulations completed just prior to flight test revealed that the system had a slowly divergent first order mode. This problem was not predicted with the short period approximation of the aircraft model used in design and during initial ground tests. The problem was only found when the phugoid mode was included during the final ground simulation 1 day prior to the start of flight test.

<u>H2INI</u>.

The evaluation pilots performed eight straight-in and eight horizontal offset landings with the H2INI flight control configuration. Figures D9 through D1 illustrate the C-H and PIO histograms. Pilot one consistently rated this configuration Level II while pilot three consistently rated this configuration Level I. Pilot two rated the configuration Level I for the straight-in task, but gave both Level I and Level II ratings for the horizontal offset task. The PIO ratings by all the pilots fell between PIO 1 and PIO 3 with the majority of the ratings PIO 1 or PIO 2. The C-H and PIO ratings were worse for the horizontal offset task than they were for the straight-in task. This configuration also received poorer ratings under higher winds (Appendix E).

All the pilots liked the short-term pitch response, describing it as smooth and predictable. All three pilots could change the pitch attitude rapidly; however, pilot one commented on one landing where the response felt sluggish. No explanation was found for this comment. All three pilots flew this configuration with winds from 8 to 20 knots. During these flights, each pilot noticed an airspeed sensitivity and divergence similar to the H2AOA configuration, but not as objectionable. Under these windy conditions, pilot three also noticed negative speed stability during the go-around portion of a low approach. Pilot two's second look at the configuration occurred on a day when the winds varied from calm to 10 knots. During this sortie, pilot two only noticed the divergent characteristics when the wind was above 5 knots. Pilot two gave the configuration Level II C-H ratings during the windy conditions, due to the increased workload required to maintain airspeed. Pilot one was able to consistently achieve desired performance with this configuration but found the divergent nature of the system to be objectionable enough to warrant Level II C-H ratings. All the pilots noticed a slight tendency for the nose to pitch down during the landing roll. This pitching moment was more benign than the H2AOA configuration.

Like the H2AOA design, the slightly divergent nature of the aircraft with this flight control configuration was predicted during the final ground test. Overall, the slight divergent nature of the pitch response had an impact on the landing tasks. The H2INI configuration was rated between Level I and Level II.

H2AIN.

The evaluation pilots performed six straight-in and six horizontal offset landings with the H2AIN flight control configuration. Figures D13 through D16 illustrate the C-H and PIO histograms. The C-H ratings for this configuration ranged from C-H 3 to C-H 5 with the majority of the ratings being C-H 4. The PIO ratings for this configuration ranged from PIO 1 to PIO 3 with the majority of ratings being PIO 2. Although each pilot's C-H and PIO ratings varied, the overall distribution of the ratings were virtually the same for both the straight-in and horizontal offset tasks. None of the ratings were affected by the winds (Appendix E).

The H2AIN flight control configuration exhibited many of the same characteristics as the H2INI flight control configuration, although to a greater degree. This similarity was logical as the only difference between H2AIN and H2INI flight control conditions was a filter placed in the command channel of the H2AIN configuration. This filter was designed to make the original pitch rate tracking system behave more like an AOA tracking system. While this objective was achieved, the filter made the initial pitch response more sluggish. The pilots did not like this sluggishness and commented that the pitch response "takes a while to get going." The sluggishness was very noticeable when the stick was displaced slightly and held while the pitch response was observed. The pitch rate accelerated slowly until it stabilized at a steady-state value. The added filter in the H2AIN design may have caused the divergent nature of the system to be more noticeable. All the pilots felt that the long-term pitch axis response diverged in a manner similar to the H2AOA flight control configuration, although at a slower rate. This divergence made the configuration very sensitive to airspeed deviations from trim; therefore, pilot workload increased trying to maintain airspeed. Pilot two commented that the speed was 5 KIAS below trim airspeed during the approach, and that the stick had to be pushed; however, during the flare, all the pilots commented that the nose felt heavy. This made the aircraft hard to control precisely in the flare and forced the pilots to adopt a low-gain technique to obtain desired performance. The pilots were unable to keep the nose from dropping after landing, due to the heavy stick forces. This nosedown motion was worse than the H2INI flight control configuration, but not as bad as the H2AOA flight control configuration. Like the H2AOA and H2INI flight control configurations, the H2AIN flight control configuration was found to be divergent during the final ground test. Both the sluggishness of the pitch response and the divergent nature of the system had an impact on the landing tasks. The H2INI flight control configuration was rated between Level I and Level II.

MXAOA.

The evaluation pilots performed 11 straight-in and 10 horizontal offset landings with the MXAOA flight control configuration. Figures D17 through D20 illustrate the C-H and PIO histograms. Pilots one and two consistently rated this configuration Level I while pilot three consistently rated this configuration Level II. The PIO ratings ranged from PIO 1 to PIO 3. The winds did not have an effect on the C-H and PIO ratings (Appendix E).

The MXAOA flight control configuration was stable with no tendency for a long-term pitch divergence. Stability was predicted for this configuration during the final ground test. While the long-term pitch response was acceptable, the pilots felt that the short-term pitch response was fast and too lightly damped. Each of the pilots noticed a small overshoot of the aircraft pitch response which they described as a "pitch bobble." This bobble could be eliminated by anticipating the aircrafts response and adjusting the size of the input accordingly. Pilots one and two were able to eliminate this pitch overshoot with minimal compensation and, thus, rated the configuration a Level I C-H. Pilot three, however, found the pitch bobble objectionable during the flare and had to sacrifice desired performance on several landings. During these landings, the pilot cautiously delayed power reduction until the pitch bobble damped out. This caused pilot three to carry excess power into the flare and float beyond the desired touchdown point. On the landings when pilot three was able to achieve desired performance, the workload was still high enough to warrant Level II ratings. The pitch sensitivity was also noted during HQDT testing. Both pilots two and three gave the configuration PIO 4 ratings during HQDT tasks. The HQDT results indicated that this configuration was PIO prone to large amplitude, high frequency inputs. This tendency may have been the cause of the unwanted pitch motions seen by pilot three. Overall, the pitch sensitivity of this FCS had an impact on some of the landings, and the MXAOA flight control configuration was rated between Level I and Level II.

SUMMARY

Ground verification and validation of design models used is a mandatory step that should be completed early in the flight test process. The HAVE INFINITY I test team discovered problems in the verification phase, 1 day prior to flight test, that plagued them throughout their flight test program. An initial trip to Calspan Corporation, Buffalo, New York, 2 months prior to flight test, was a high priority for the HAVE INFINITY II limited flight test; however, the aircraft model did not include the phugoid mode during this simulation. While verification of the five control configurations flight tested was successful for the HAVE INFINITY II test program, the problem of the unmodeled phugoid discovered during ground validation testing 1 day prior to flight test could not be overcome in the time available. The Calspan Learjet did an excellent job of simulation on the ground and in the air. Most of the Level II comments related to the instability in the H2INI, H2AIN, and H2AOA designs were attributed to the phugoid mode. The H2INI, H2AIN, and H2AOA designs produced acceptable, but unsatisfactory, handling qualities, and may have been closer to satisfactory had the phugoid mode been included in the design aircraft model. The results of this program simply reinforce that early verification and validation of design models through the use of the highest fidelity simulation possible, must be supported and required by the Responsible Test Organization.

CONCLUSIONS

Model verification and validation and subsequent flight testing allowed for a satisfactory evaluation of the handling qualities of the HAVE INFINITY II flight control system (FCS) designs. The HAVE INFINITY II flight control laws were correctly implemented and flown on the Calspan Variable Stability System Learjet. The tool used in achieving this was the use of ground and in-flight verification and validation simulation of the HAVE INFINITY II flight control laws tested. The Calspan Learjet simulation results were very similar on the ground and in the air. This was confirmed by the correlation of the ground and flight test time response matches and pilot comments. Details are discussed in the Model Verification and Validation Results section of this report. Handling qualities results indicated that the optimal design methods used gave Level II or better, and handling qualities PIO ratings of 4 or better. H2AOA had two PIO ratings while all other configuration ratings ranged between 1 and 3. Most of the Level II comments related to the instability in the H2INI, H2AIN, and H2AOA designs caused by the phugoid mode that was unaccounted for in the design process. These designs may have been rated closer to Level I if the phugoid had been included in the design aircraft model.

Proper verification and validation of all models used in the design process is critical. It is paramount the Responsible Test Organization (RTO) require and support these efforts. The earlier this can be accomplished prior to flight test, the more flexibility the RTO has to implement required changes and avoid the fly-fix-fly approach.

This lesson was learned by both the HAVE INFINITY I test team in the verification phase and the HAVE INFINITY II test team in the validation phase.

This page intentionally left blank.

REFERENCES

1. Anderson, John, Captain, USAF, *Flight Test and Handling Qualities Analysis of a Longitudinal Flight Control System Using Multiobjective Control Design Techniques*, Master's Thesis Draft, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, January 1997.

2. Cooper, George E. and Harper, Robert P., *The Use of Pilot Rating In The Evaluation of Aircraft Handling Qualities*, NASA Technical Note D-5153, National Aeronautics and Space Administration, Washington DC, April 1969.

3. Military Standard Flying Qualities of Piloted Aircraft, MIL-STD-1797A, ASD/ENES, Wright-Patterson AFB, Ohio, 30 January 1990.

4. *USAF TPS Flying Qualities Phase Text Vol. IV, Flying Qualities Testing*, USAF TPS/EDF, Edwards AFB, California, 1 June 1995.

5. Learjet Flight Syllabus and Background Material for the U.S. Air Force/U.S. Navy Test Pilot School Variable Stability Programs. ed. Buethe, Scott, February 1994.

This page intentionally left blank.

APPENDIX A

DETAILED TEST ITEM DESCRIPTION

This page intentionally left blank.

DETAILED TEST ITEM DESCRIPTION

The Learjet Model 24 has been highly modified to serve as a three-axis in-flight simulator for use as a teaching aid at the USAF and USN Test Pilot Schools. It is operated by Calspan under an experimental license from FAA (Reference 5).

The variable stability controls are installed in the right seat. The system can be disengaged by any of three manual disconnect switches, which are installed on each of the two control stick/yoke and on the glareshield. In addition, automatic safety trips are provided. In the event of incapacitation of the safety pilot or certain control cable failures, the aircraft can be flown by the evaluation pilot as a nearly normal Learjet using the Variable Stability System (VSS) in the fly-by-wire (FBW) mode. All basic Learjet systems are available in the FBW mode except for nosewheel steering.

The handling qualities are those of the basic aircraft with the yaw damper on. There are no safety trips in the emergency FBW mode. Hydraulic power for the variable stability actuators was obtained from the existing Learjet hydraulic system, which provides 4 gallons per minute, per engine. Estimated maximum flow demand to operate all servoactuators is 3.35 gallons per minute. Maximum demand for normal Learjet flaps, spoilers, gear, and brakes were under 4 gallons per minute. Solenoid operated valves to the variable stability actuators are designed fail safe to prevent hydraulic locks on the actuators.

Operating limitations that apply to the Learjet are listed in Table A1.

Table A1
LEARJET LIMITATIONS

	VSS Off	VSS On
Speed Limitations	356 KIAS/0.82 Mach number	325 KIAS
g Limitations	+4.4 to -1.0	+2.8 to +0.15

Note: VSS - Variable Stability System

This page intentionally left blank.

APPENDIX B

TEST CARDS AND COOPER-HARPER AND PILOT-IN-THE-LOOP OSCILLATION RATING SCALES

This page intentionally left blank.

TEST CARDS AND COOPER-HARPER AND PILOT-IN-THE-LOOP OSCILLATION RATING SCALES

√ In / Takeoff	HAVE INFINITY II JON: M96J0200	FREQ

C/S	A/C	TAIL	OPS #	CREW
Cobra	LJ-24	0101		
Target Cobra	**A/C** C-23	**TAIL**	**OPS #**	**CREW**

T/O GW	FUEL	T/O CG	DATE	LAKEBEDS

ATIS	WINDS	TEMP	ALT	PA	RUNWAY

JOKER	BINGO	TAKEOFF	LAND

CARD #	EVENT	ALT A/S	NOTES
	HQDT 1000' trail	8K' 135	
	HQDT close formation	8K' 135	
	LANDINGS normal horiz. offset vert. offset		

Preflight Checks
1. Trim settings - set
2. Configuration Control Panel - set

Post Configuration Change Checks
1. Configuration - confirm
2. New stick gain - set
3. Low bandwidth inputs - response as expected

Config 196	
EAA	500
EAD	500
EOO	500
EEF	235
EFC	167
EF2	075
EF5	020
AAF	440
AFC	286
DBD	800

Figure B1 Test Card 1

COMMENT CARD			
C-H RATING			
PIO RATING			
Predictability	good	|--------|--------|	sucks
Initial Delay	none	|--------|--------|	gross
Onset of initial response	smooth	|--------|--------|	abrupt
Sensitivity (speed of response)	too sensitive	|--------|--------|	sluggish
Linearity of response	linear	|--------|--------|	non-linear
Sensitivity to pilot aggressiveness	insensitive	|--------|--------|	sensitive
Ability to change pitch attitude rapidly	easy	|--------|--------|	hard
Tendency to overshoot pitch attitude	none	|--------|--------|	large
Tendency to undershoot pitch attitude	none	|--------|--------|	large
Overall precision of control	precise	|--------|--------|	sloppy
Ability to correct errors	easy	|--------|--------|	hard
Control forces	too low	|--------|--------|	too high
Control displacements	too much	|--------|--------|	too little
FACTORS EFFECTING RESULTS Gusty Winds / Crosswind / Turbulence / Pilot Technique / Fuel			
REVIEW PILOT RATING			

Figure B2 Test Card 2

HAVE INFINITY II TEST CARD **HORIZONTAL OFFSET LDG TASK**			DATE	CARD#
EVAL PILOT			PROFILE	
SAFETY PILOT			CONFIGURATION	
TEST CONDUCTOR			TEST POINT	
WINDS:		TURB	RWY	
SETUP 4.3K, 130 kt	FUEL	APP SPEED	TD SPEED	

LIMITS: GEAR - FLAPS -
DO NOT ENGAGE VSS UNTIL REACHING PATTERN ALTITUDE

TASK: Intercept ILS glideslope and offset 300' laterally. At 200' AGL, correct to centerline by 100' AGL using 30 to 45 degrees of bank within 3 seconds. Intercept a visual glidepath to touchdown in desired box.

Notes:

Figure B3 Test Card 3

COOPER-HARPER RATING

A Cooper-Harper (C-H) rating was given for each landing task (Figure B4). Figure B2 was used by the test conductor to aid the pilot in determining the appropriate C-H rating.

COOPER-HARPER RATING SCALE

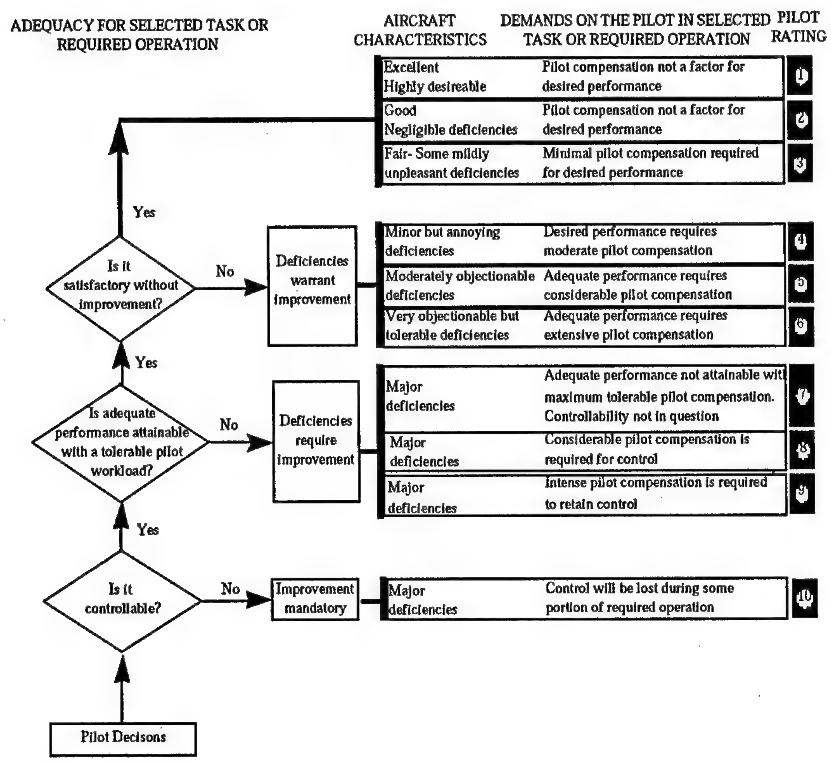

Figure B4 Cooper-Harper Rating Scale

Pilot-in-the-loop Oscillation Rating:

A pilot-in-the-loop oscillation (PIO) rating was given for handling qualities during tracking evaluations with a C-23 target aircraft and for each landing task (Figure B5). Figure B2 was used by the test conductor to aid the pilot in determining the appropriate PIO rating. Descriptions for the PIO ratings are shown in Figure B6.

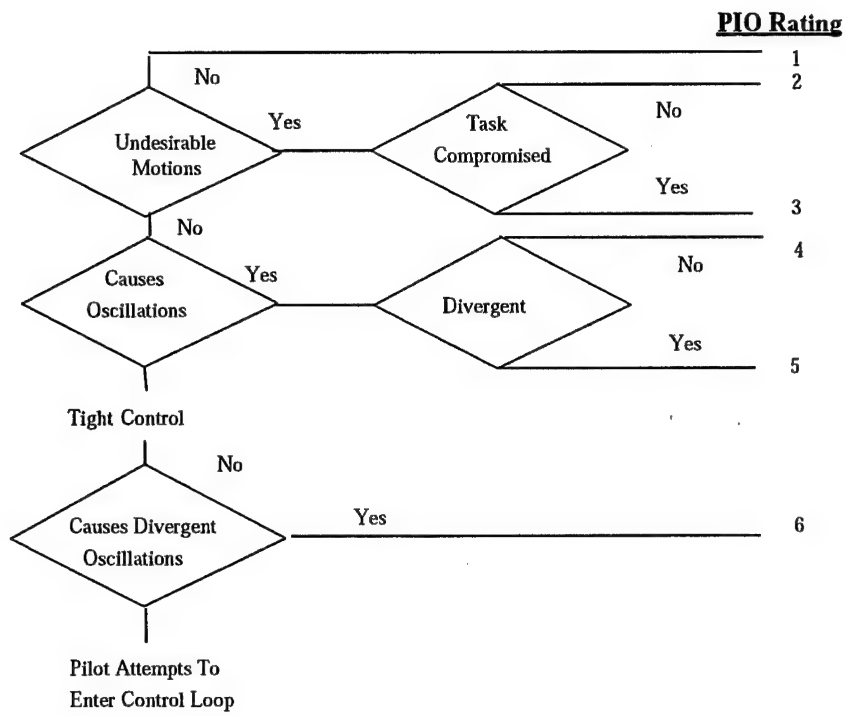

Figure B5 Pilot-in-the-Loop Oscillation Rating Decision Tree

Pilot-in-the-Loop Oscillation Scale	
Description	Numerical Rating
No tendency for pilot to induce undesirable motions.	1
Undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot techniques.	2
Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated, but only at sacrifice to task performance or through considerable pilot attention and effort.	3
Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.	4
Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open loop by releasing or freezing the stick.	5
Disturbance or normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing the stick.	6

Figure B6 Pilot-in-the-Loop Oscillation Rating Scale

APPENDIX C

MODEL VERIFICATION AND VALIDATION

This page intentionally left blank.

MODEL VERIFICATION AND VALIDATION

The pole-zero notation used in Tables C1 through C7 was standard Test Pilot School (TPS) shorthand for expressing the poles and zeros of a transfer function. This notation listed first order poles and zeros as positive if stable, and negative if unstable. For example, (2.0) expresses the Laplace transform complex variable (s)-domain monomial s+2. Setting this expression equal to zero results in a pole of s = -2. Second order pole and zero pairs are expressed as an ideal damping ratio (ζ) and the pole or zero natural frequency (ω_n) in brackets. For example; [0.5 4] would express the s-domain polynomial $s^2+4s+16$, which is of the form $s^2+2\zeta\omega_n+\omega_n^2$. The gain is the result setting s=0 in the numerator and denominator of the transfer function. The optimal control transfer functions are divided into the three input channels of the control law: command, pitch rate (q), and angle of attack (α). Ground and flight test validation data are shown in Figures C1 through C11. Tables 8 through 12 present the closed-loop pole analysis for the five HAVE INFINITY II flight control configurations.

Table C1
POLE-ZERO VERIFICATION - AIRCRAFT

	Design Model	Implementation Model
Poles (rad/sec)	(0.3029) (-1.4971)	(0.3028) (-1.4970)
Zeros (rad/sec)	(-0.8329) (-70.2309)	(-0.8329) (-70.2310)

Table C2
POLE-ZERO VERIFICATION - CLASSIC

	Design Model[1]	Implementation Model
Gain - K_q Pitch Rate Feedback Loop	0.441	0.441
Gain - K_a AOA Feedback Loop	1.600	1.600

Notes 1. K_q - pitch rate gain
2. K_a - angle-of-attack gain
3. AOA - angle of attack

[1]There was no dynamic compensation used in this design. Only the feedback gains shown above were used to produce the CLASSIC design.

Table C3
POLE-ZERO VERIFICATION - H2AOA

	Design Model	Implementation Model
Poles (rad/sec) All Channels	(7.2304) (4.4631) [0.53, 2.30]	(7.2304) (4.4631) [0.53, 2.30]
Zeros (rad/sec) Command Channel	(6.6167) (1.5171) (0.2990)	(6.6167) (1.5171) (0.2990)
Gain Command Channel	-14.5252	-14.5252
Zeros (rad/sec) Pitch Rate Channel	(1.5461) [0.53, 2.30]	(1.5461) [0.53, 2.30]
Gain - q Channel	11.0656	11.0656
Zeros (rad/sec) AOA Channel	(1.4962) [0.53, 2.30]	(1.4962) [0.53, 2.30]
Gain - α Channel	0.1054	0.1054

Notes: 1. q - pitch rate
2. AOA - angle of attack
3. α - angle of attack

Table C4
POLE-ZERO VERIFICATION - H2AIN

	Design Model	Implementation Model
Poles (rad/sec) Command Channel	(6.0) (0.8405) [0.9999, 31.6083]	(6.0) (0.8405) [0.9999, 31.6083]
Zeros (rad/sec) Command Channel	(21.4843) (1.5171) (0.2990)	(21.4843) (1.5171) (0.2990)
Gain Command Channel	-107.42	-107.42
Zeros (rad/sec) Pitch Rate Channel	(6.0) (4.0809) (1.4402)	(6.0) (4.0809) (1.4402)
Gain - q Channel	58.71	58.71
Zeros (rad/sec) AOA Channel	(6.0) (3.9061) (1.5840)	-0.8329 -70.2310
Gain - α Channel	0.50	0.4999

Notes: 1. q - pitch rate
2. AOA - angle of attack
3. α - angle of attack

Table C5
POLE-ZERO VERIFICATION - H2INI

	Design Model	Implementation Model
Poles (rad/sec) Command Channel	(6.0) (0.8405) [0.9999, 31.6083]	(6.0) (0.8405) [0.9999, 31.6083]
Zeros (rad/sec) Command Channel	(21.4843) (1.5171) (0.2990)	(21.4843) (1.5171) (0.2990)
Gain Command Channel	-107.42	-107.42
Zeros (rad/sec) Pitch Rate Channel	(6.0) (4.0809) (1.4402)	(6.0) (4.0809) (1.4402)
Gain - q Channel	58.71	58.71
Zeros (rad/sec) AOA Channel	(6.0) (3.9061) (1.5840)	-0.8329 -70.2310
Gain - α Channel	0.50	0.4999

Notes: 1. q - pitch rate
2. AOA - angle of attack
3. α - angle of attack

Table C6
POLE-ZERO VERIFICATION - MXAOA

	Design Model	Implementation Model
Poles (rad/sec) Command Channel	(85.4428) [0.6456, 25.3192] [0.9375, 5.1344] [0.9454, 0.3811]	(85.4428) [0.6456, 25.3192] [0.9375, 5.1344] [0.9454, 0.3811]
Zeros (rad/sec) Command Channel	(53.0559) (1.3192) (0.8195) (0.4175) [0.7064, 24.8286]	(53.0559) (1.3192) (0.8195) (0.4175) [0.7064, 24.8286]
Gain Command Channel	-36.8823	-36.8823
Zeros (rad/sec) Pitch Rate Channel	(0.8936) (0.4391) [0.7898, 34.0126] [0.8267, 5.3258]	(0.8936) (0.4391) [0.7898, 34.0126] [0.8267, 5.3258]
Gain - q Channel	43.4441	43.4441
Zeros (rad/sec) AOA Channel	(60.5737) (4.9107) [0.6775, 24.5839] [0.9705, 0.4375]	(60.5737) (4.9107) [0.6775, 24.5839] [0.9705, 0.4375]
dc Gain - α Channel	3.5357	3.5357

Notes: 1. q - pitch rate
2. AOA - angle of attack
3. α - angle of attack

Table C7
POLE-ZERO VERIFICATION - MXINI

	Design Model	Implementation Model
Poles (rad/sec) Command Channel	(1.9051) (84.9036) [0.6906, 29.4591] [0.1563, 1.3921]	(1.9051) (84.9036) [0.6906, 29.4591] [0.1563, 1.3921]
Zeros (rad/sec) Command Channel	(1.8081) (0.7184) (216.1494) [0.3888, 28.1514]	(1.8081) (0.7184) (216.1494) [0.3888, 28.1514]
Gain Command Channel	-0.5776	-0.5776
Zeros (rad/sec) Pitch Rate Channel	(2.4557) [0.8242, 55.7059] [0.6217, 1.1901]	(2.4557) [0.8242, 55.7059] [0.6217, 1.1901]
Gain - q Channel	15.6905	15.6905
Zeros (rad/sec) AOA Channel	(6.3463) [0.2511, 1.6603] [0.6896, 44.3650]	[0.2511, 1.6603] [0.6896, 44.3650]
Poles (rad/sec) α poles	(1.9051) (84.9036) [0.6906, 29.4591] [0.1563, 1.3921]	(0.8015) (2.4179) (1.0) [0.6905, 29.4951]
Gain - α Channel	1.5090	1.5090

Notes: 1. q - pitch rate
2. AOA - angle of attack
3. α - angle of attack

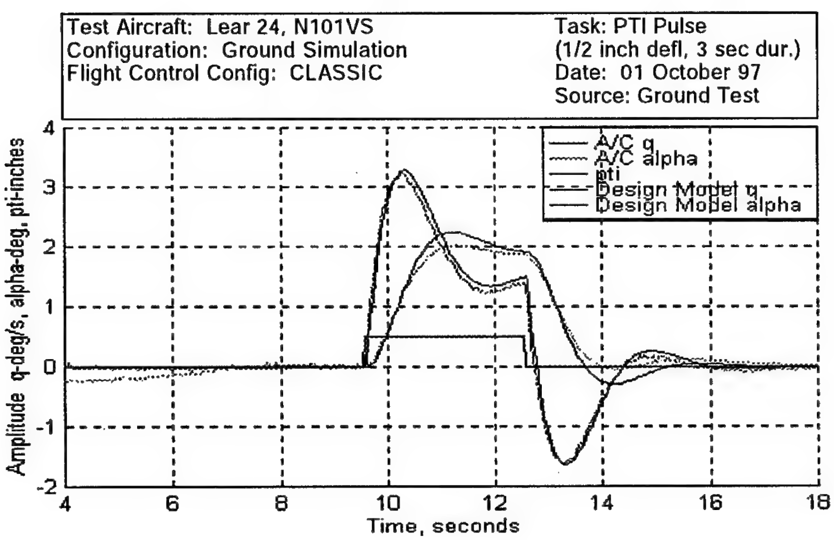

Figure C1 Ground Test Closed-Loop q and α Time Responses - CLASSIC

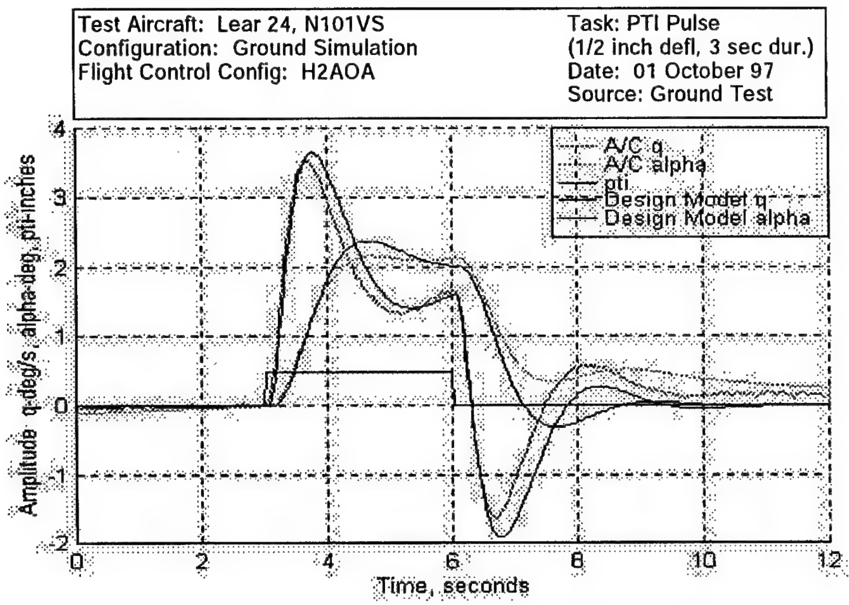

Figure C2 Ground Test Closed-Loop q and α Time Responses - H2AOA

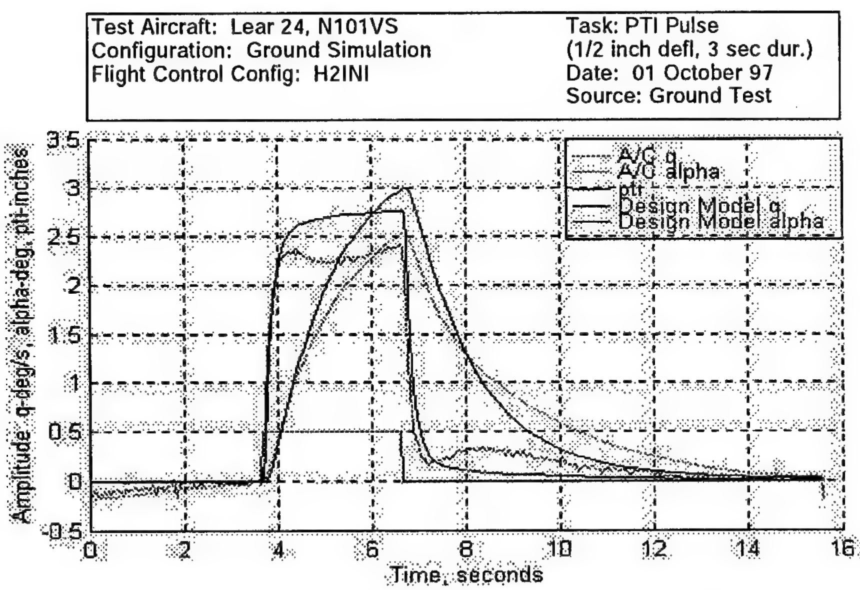

Figure C3 Ground Test Closed-Loop q and α Time Responses - H2INI

Test Aircraft: Lear 24, N101VS
Configuration: Ground Simulation
Flight Control Config: H2AIN

Task: PTI Pulse
(1/2 inch defl, 3 sec dur.)
Date: 01 October 97
Source: Ground Test

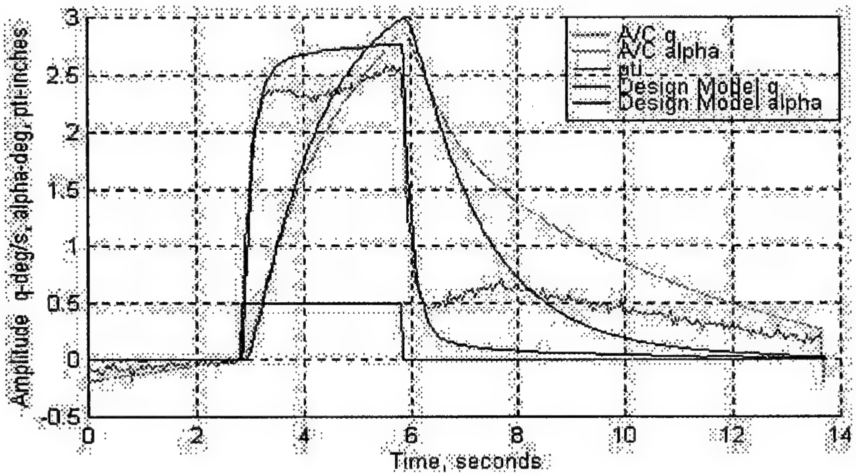

Figure C4 Ground Test Closed-Loop q and α Time Responses - H2AIN

Test Aircraft: Lear 24, N101VS
Configuration: Ground Simulation
Flight Control Config: MXAOA

Task: PTI Pulse
(1/2 inch defl, 3 sec dur.)
Date: 01 October 97
Source: Ground Test

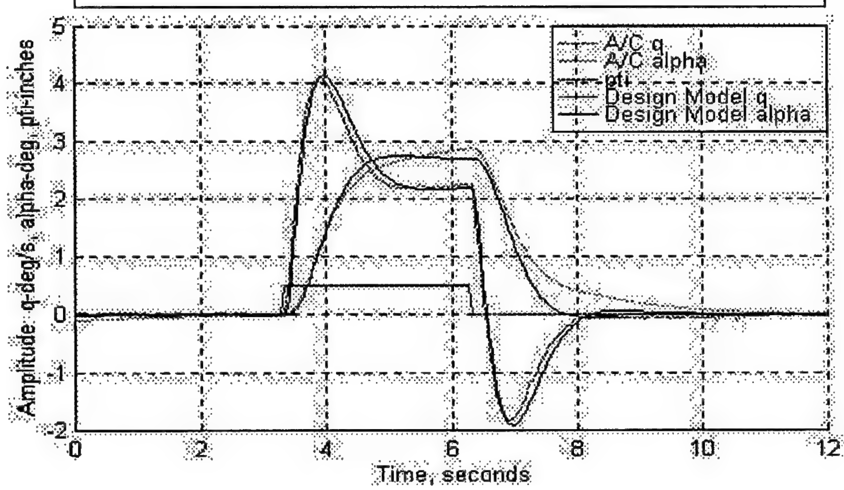

Figure C5 Ground Test Closed-Loop q and α Time Responses - MXAOA

Test Aircraft: Lear 24, N101VS Configuration: 140 KIAS, 8K MSL Gear Down, Flaps 20° Flight Control Config: N/A	Task: PTI I mpulse (1 inch stick deflection) Date: 02 Oc tober 97 Source: Fligh t Test

Figure C6 Bare Airframe Time Responses to an Impulse Input

Test Aircraft: Lear 24, N101VS Configuration: 140 KIAS, 8K MSL Gear Down, Flaps 20° Flight Control Config: CLASSIC	Task: PTI Pulse (1/2 inch, 3 sec dur.) Date: 02 October 97 Source: Flight Test

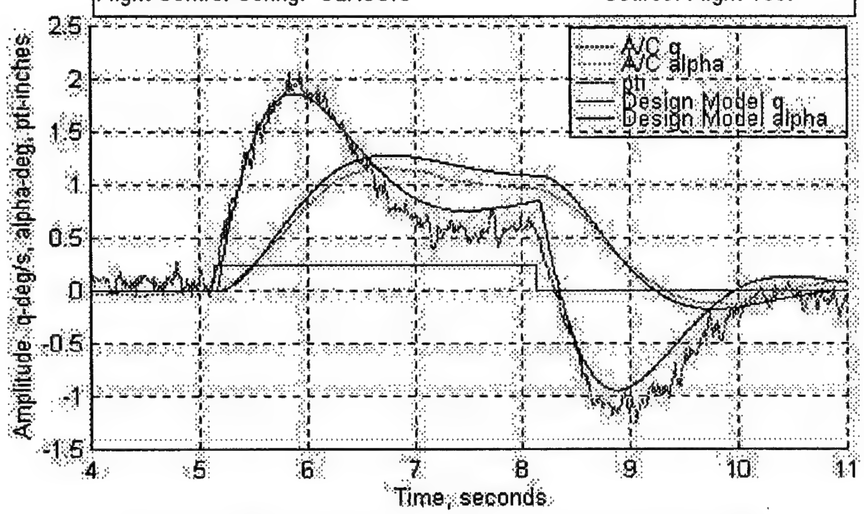

Figure C7 Flight Test Closed-Loop q and α Time Responses – CLASSIC

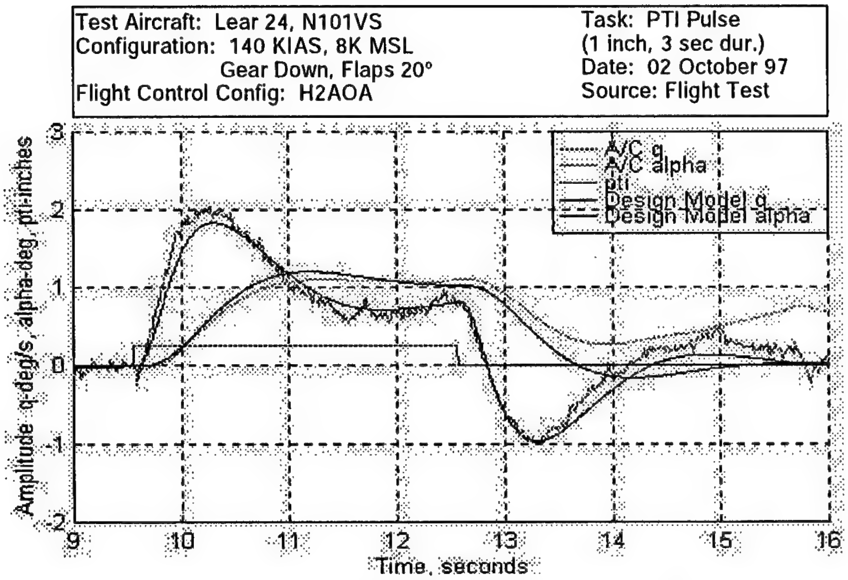

Figure C8 Flight Test Closed-Loop q and α Time Responses - H2AOA

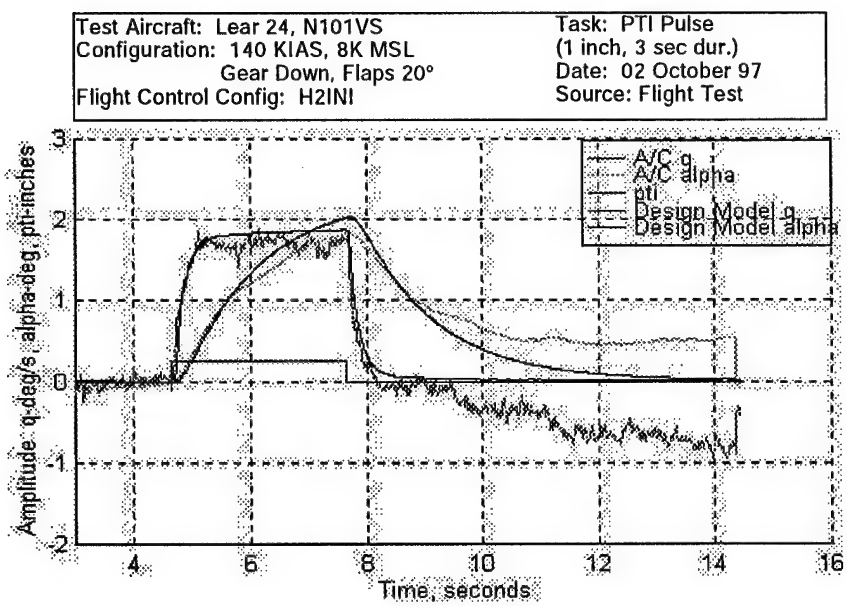

Figure C9 Flight Test Closed-Loop q and α Time Responses - H2INI

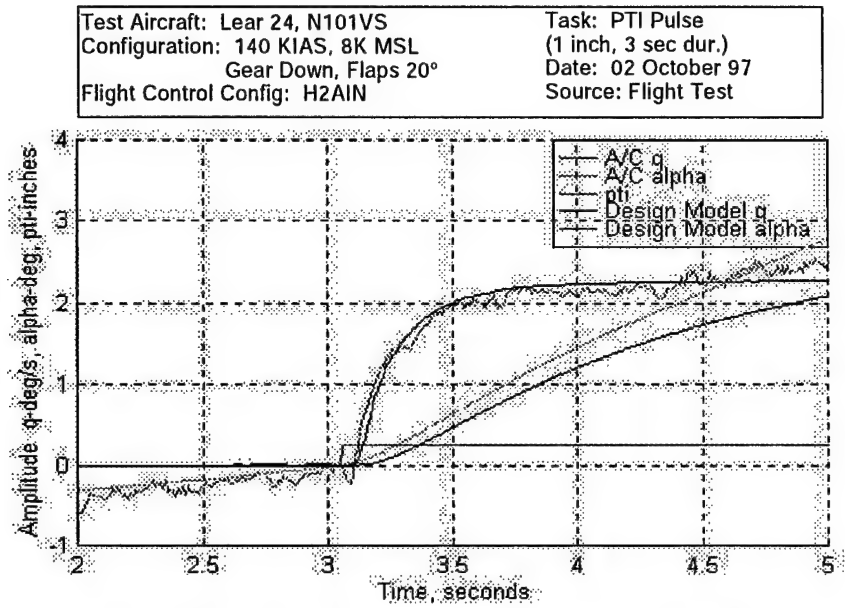

Figure C10 Flight Test Closed-Loop q and α Time Responses - H2AIN

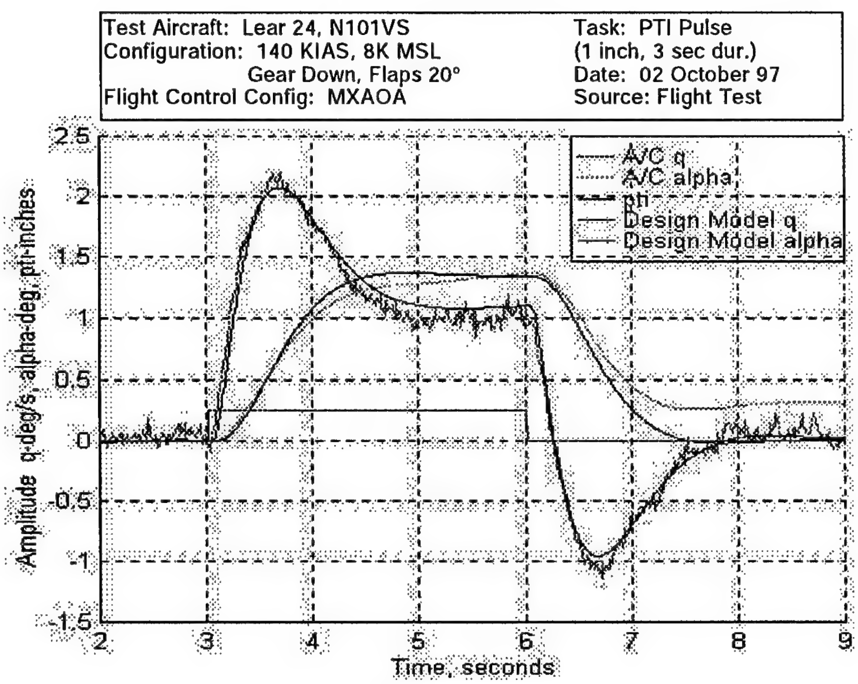

Figure C11 Flight Test Closed-Loop q and α Time Responses - MXAOA

Table C8
CLOSED-LOOP POLE ANALYSIS - CLASSIC

Closed-Loop System Poles Without Phugoid Mode	Closed-Loop System Poles With Phugoid Mode
	[0.7002, 59.1573]
[0.7001, 59.1105]	[0.5192, 2.2702]
[0.5322, 2.2772]	[0.1424, 0.1698]

Table C9
CLOSED-LOOP POLE ANALYSIS - H2AOA

Closed-Loop System Poles Without Phugoid Mode	Closed-Loop System Poles With Phugoid Mode
	[0.7038, 60.2399]
[0.7038, 60.2400]	[0.6921, 7.4256]
[0.6921, 7.4210]	(1.5127)
(1.5176)	[0.5300, 2.3000]
[0.5300, 2.3000]	[0.7308, 0.3161]
(0.3013)	(-0.1123)

Table C10
CLOSED-LOOP POLE ANALYSIS - H2AIN

Closed-Loop System Poles Without Phugoid Mode	Closed-Loop System Poles With Phugoid Mode
	[0.72, 277.41]
[0.72, 277.41]	[0.70, 60.00]
[0.70, 60.00]	[0.92, 33.43]
[0.92, 33.43]	(6.00)
(6.00)	(1.51)
(1.52)	(0.88)
(0.84)	[0.66, 0.35]
(0.30)	(-0.14)

Table C11
CLOSED-LOOP POLE ANALYSIS - H2INI

Closed-Loop System Poles Without Phugoid Mode	Closed-Loop System Poles With Phugoid Mode
	[0.72, 277.41]
[0.72, 277.41]	[0.70, 60.00]
[0.70, 60.00]	[0.92, 33.43]
[0.92, 33.43]	(6.00)
(6.00)	(1.51)
(1.52)	(0.88)
(0.84)	[0.66, 0.35]
(0.30)	(-0.14)

Table C12
CLOSED-LOOP POLE ANALYSIS - MXAOA

Closed-Loop System Poles Without Phugoid Mode	Closed-Loop System Poles With Phugoid Mode
	(84.3735)
(84.3732)	[0.7115, 59.5672]
[0.7115, 59.5679]	[0.6186, 24.3363]
[0.6186, 24.3357]	(6.8240)
(6.8060)	[0.8247, 2.6746]
[0.8230, 2.6992]	(2.0477)
(2.0367)	(0.6733)
(0.7097)	(0.4345)
(0.4358)	[0.6605, 0.0697]

This page intentionally left blank.

APPENDIX D

COOPER-HARPER AND PILOT-IN-THE-LOOP OSCILLATION HISTOGRAMS

This page intentionally left blank.

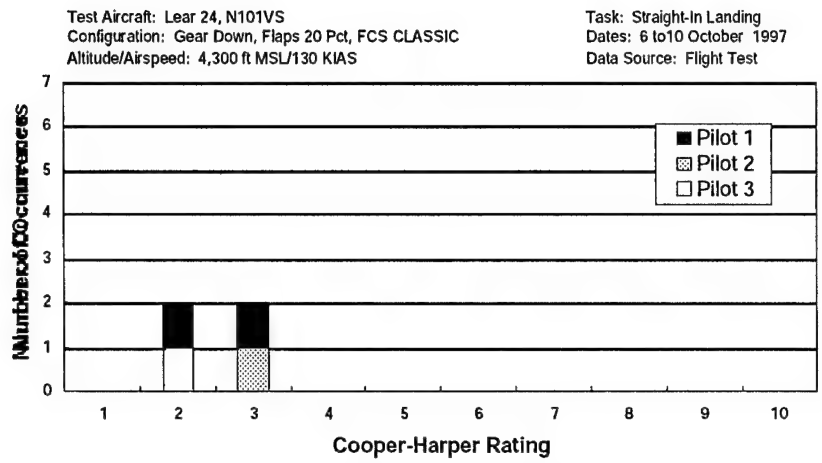

Figure D1 Straight-In Landing Cooper-Harper Ratings - CLASSIC

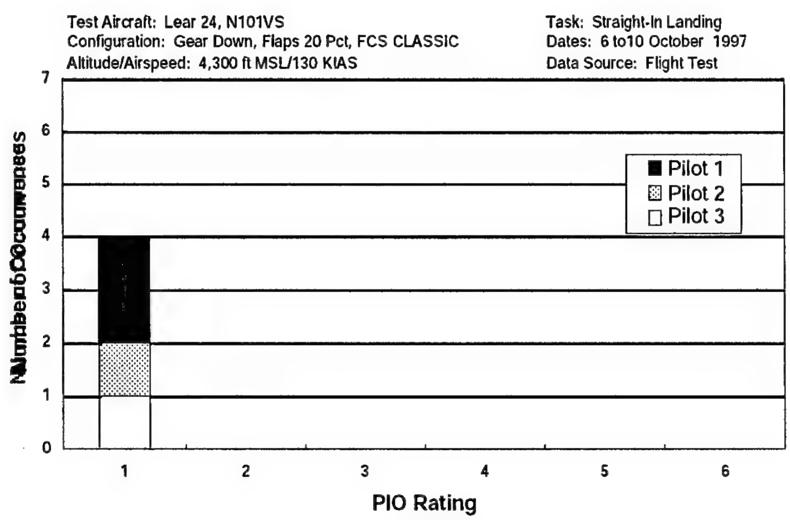

Figure D2 Straight-In Landing PIO Ratings - CLASSIC

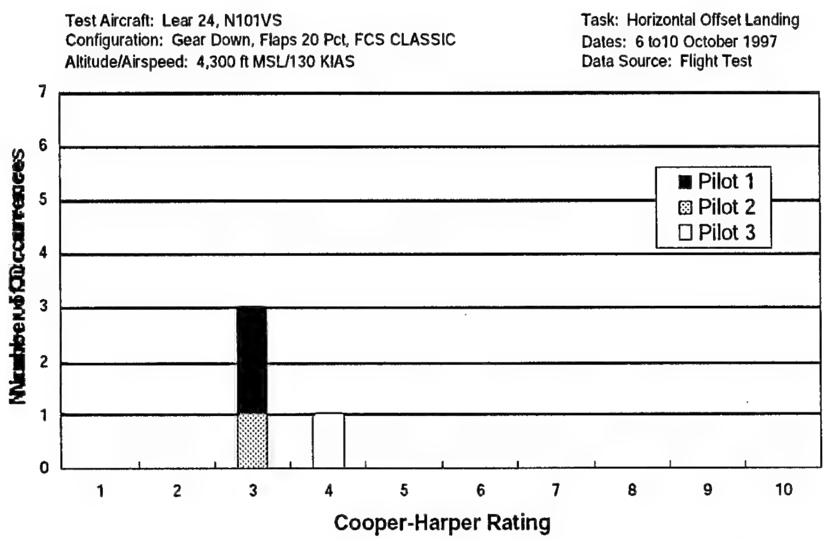

Figure D3 Horizontal Offset Landing Cooper-Harper Ratings - CLASSIC

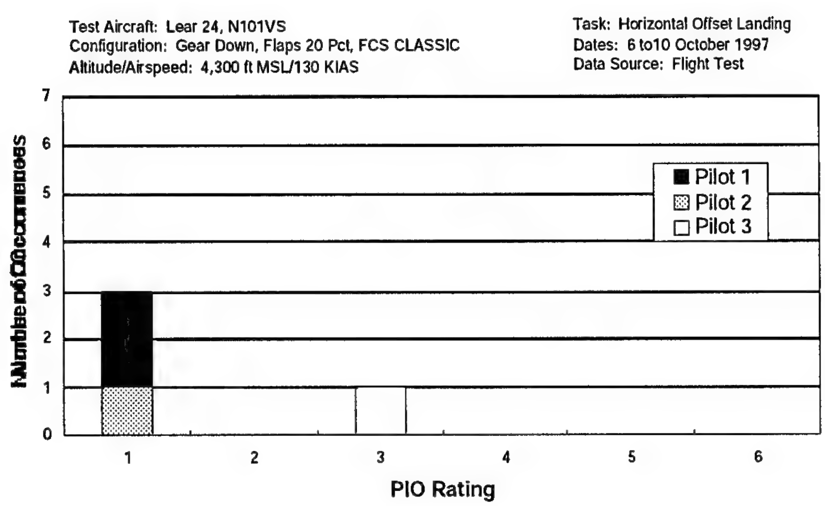

Figure D4 Horizontal Offset Landing PIO Ratings - CLASSIC

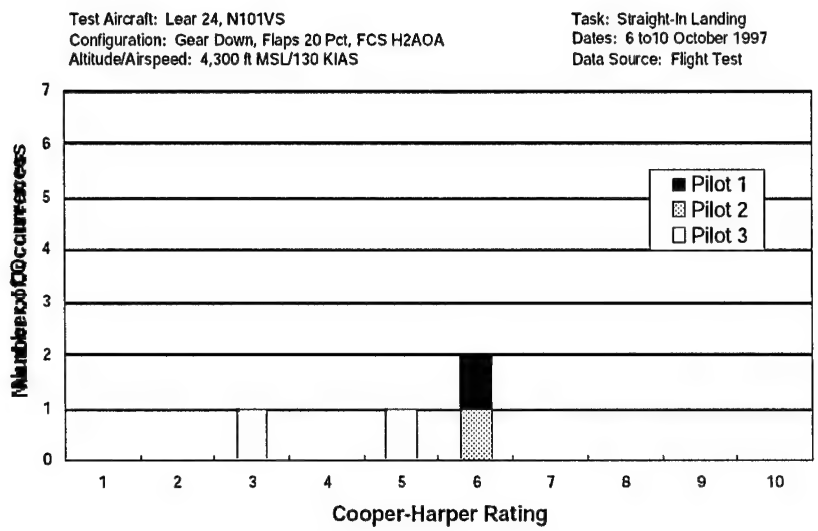

Figure D5 Straight-In Landing Cooper-Harper Ratings - H2AOA

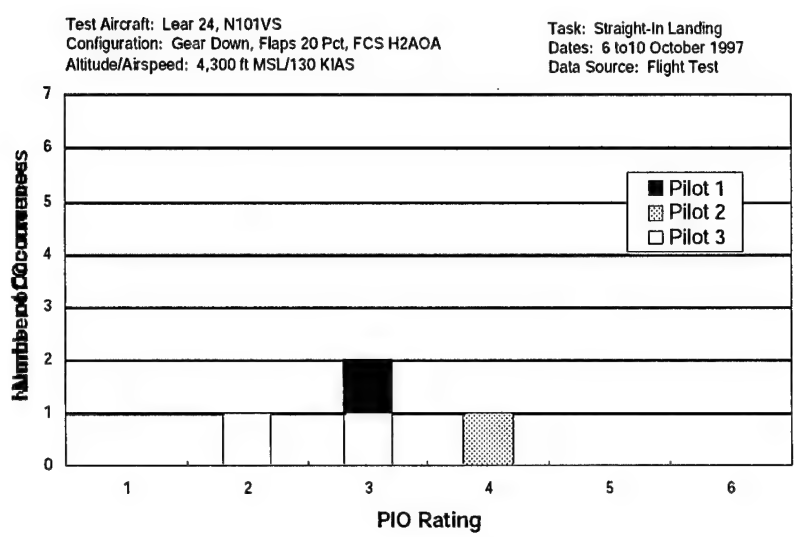

Figure D6 Straight-In Landing PIO Ratings - H2AOA

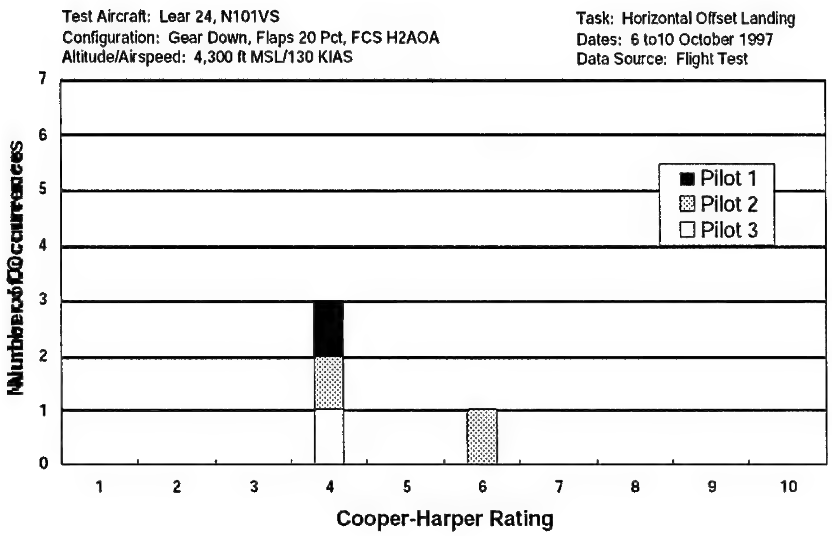

Figure D7 Horizontal Offset Landing Cooper-Harper Ratings - H2AOA

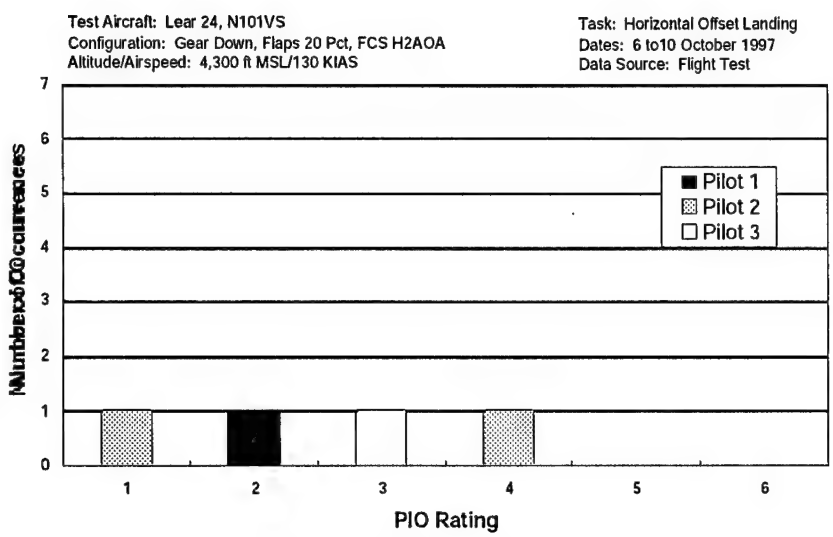

Figure D8 Horizontal Offset Landing PIO Ratings - H2AOA

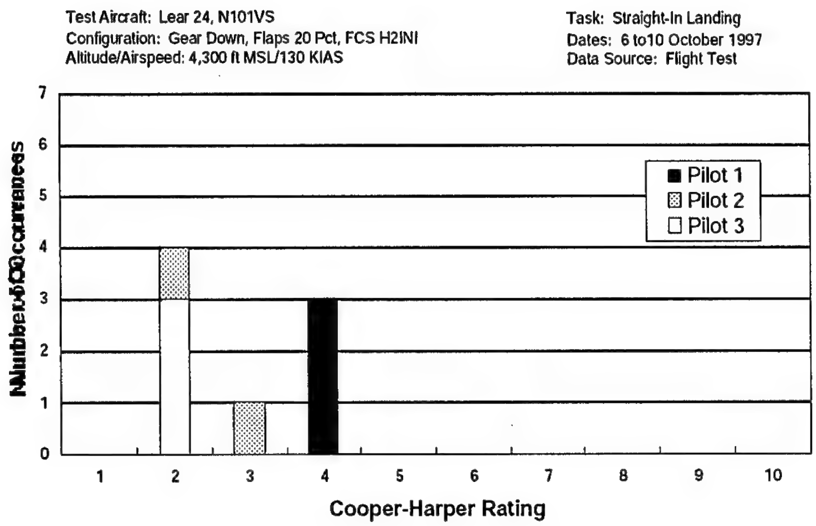

Figure D9 Straight-In Landing Cooper-Harper Ratings - H2INI

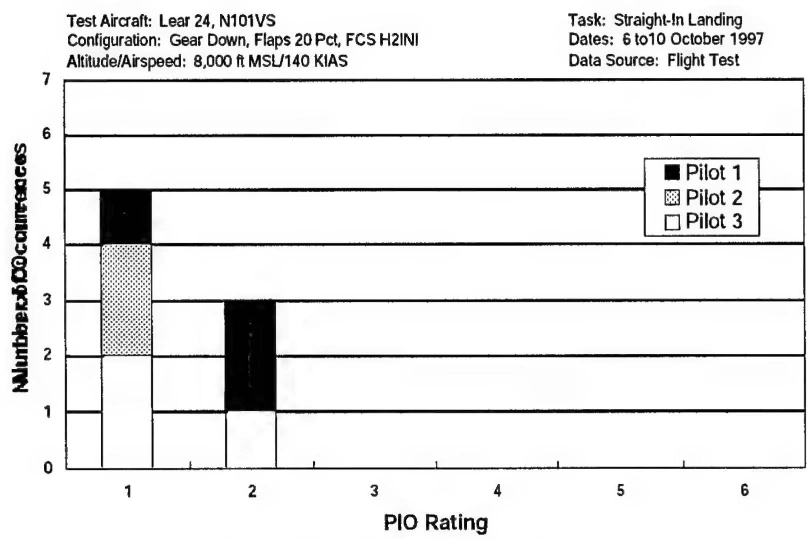

Figure D10 Straight-In Landing PIO Ratings - H2INI

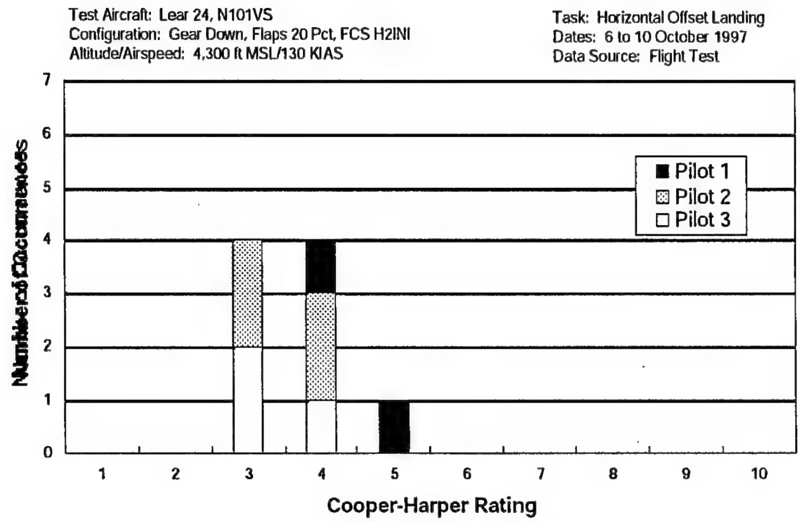

Figure D11 Horizontal Offset Landing Cooper-Harper Ratings - H2INI

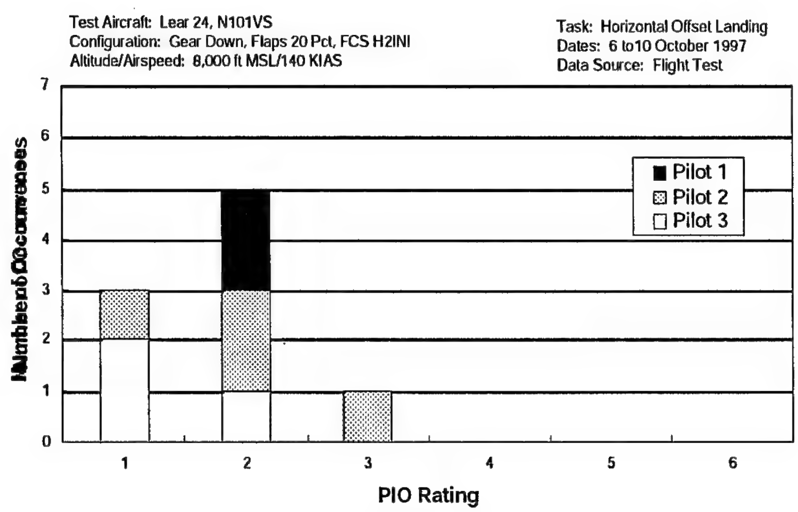

Figure D12 Horizontal Offset Landing PIO Ratings - H2INI

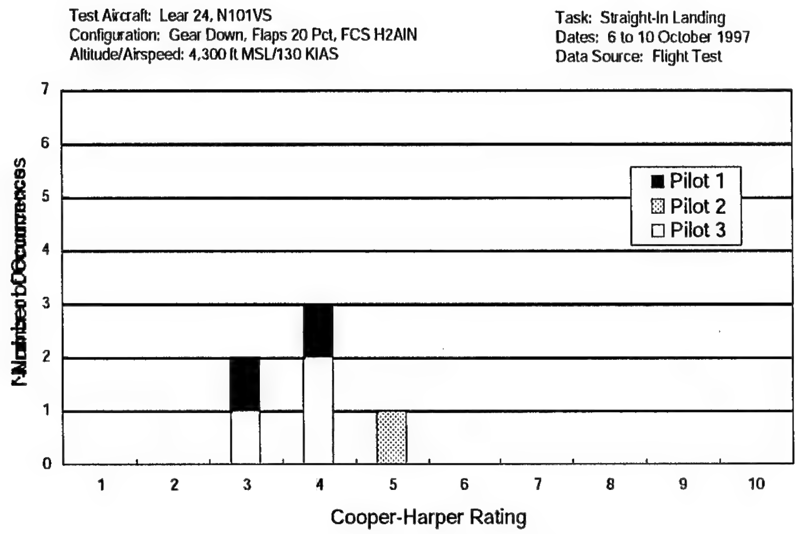

Figure D13 Straight-In Landing Cooper-Harper Ratings - H2AIN

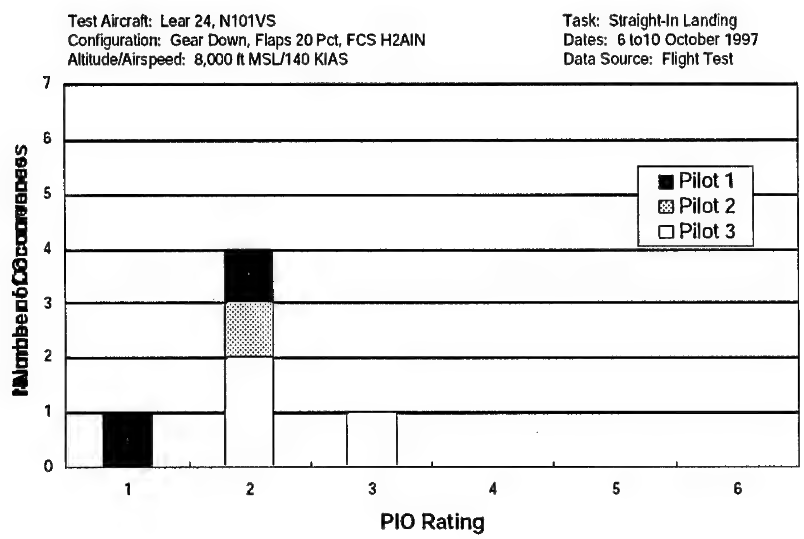

Figure D14 Straight-In Landing PIO Ratings - H2AIN

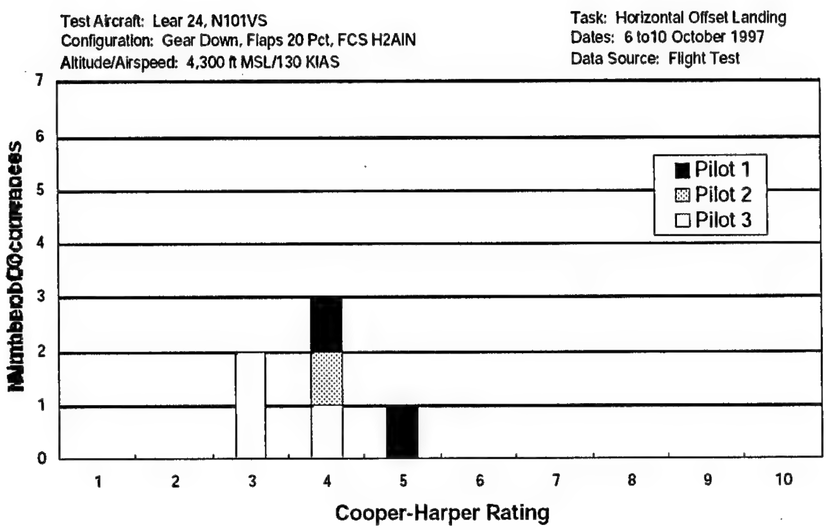

Figure D15 Horizontal Offset Landing Cooper-Harper Ratings - H2AIN

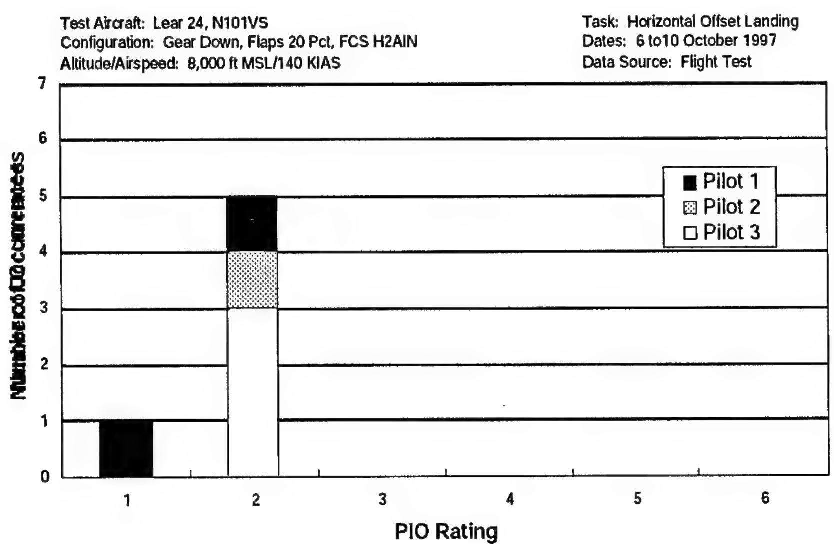

Figure D16 Horizontal Offset Landing PIO Ratings - H2AIN

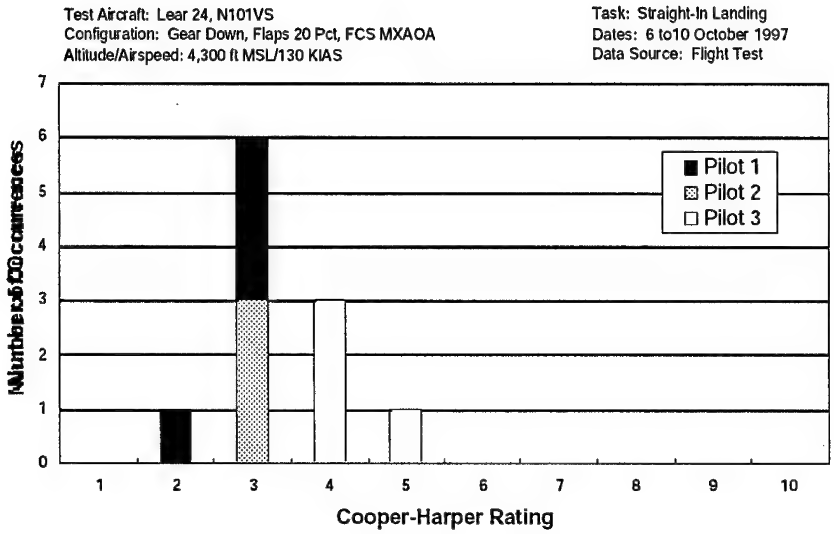

Figure D17 Straight-In Landing Cooper-Harper Ratings - MXAOA

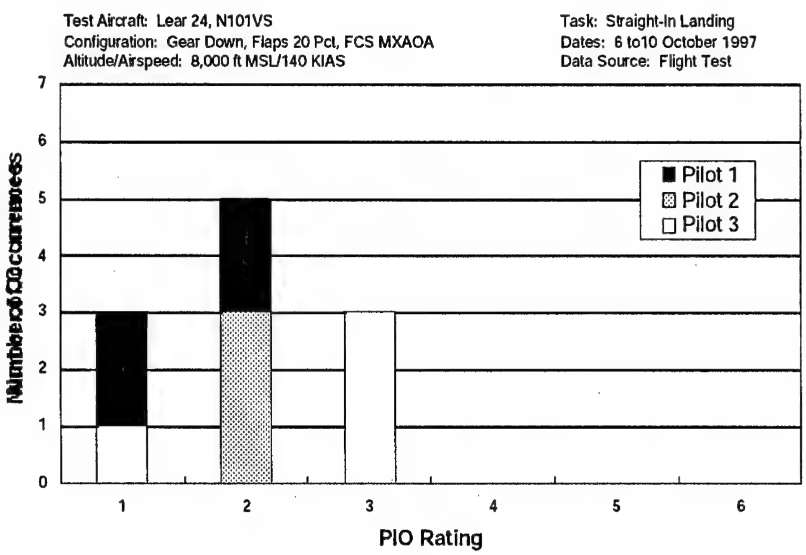

Figure D18 Straight-In Landing PIO Ratings - MXAOA

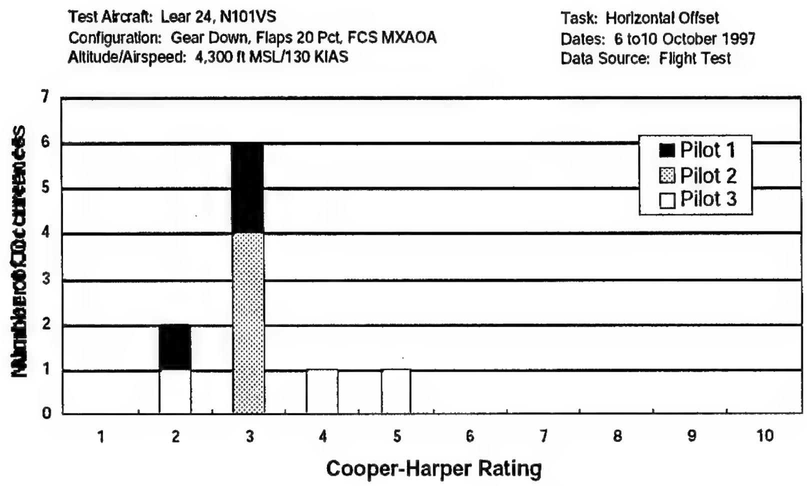

Figure D19 Horizontal Offset Landing Cooper-Harper Ratings - MXAOA

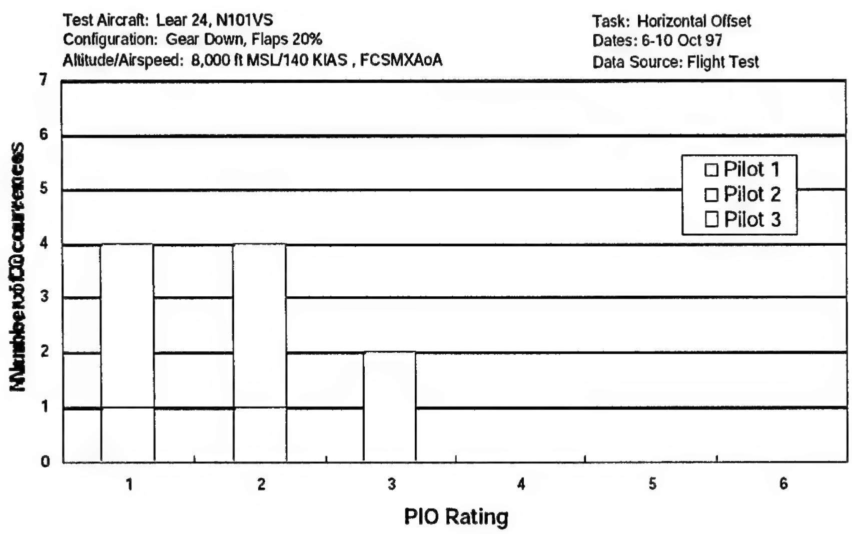

Figure D20 Horizontal Offset Landing PIO Ratings - MXAOA

APPENDIX E

QUALITATIVE LANDING DATA

This page intentionally left blank.

Flight #1 **Mission date:** 6 Oct 97 **Winds:** 240/10 **Eval Pilot:** Pilot #1 (Boe)

Appr	Task	Configuration	Landing Zone	C-H	PIO	Comments
1	St-In	H2INI	Desired	4	1	minor pitch deficiencies/heavy nose after touchdown
2	St-In	CLASSIC	Desired	3	1	could put the aircraft where the pilot wanted
3	St-In	MXAOA/H_∞ AOA Cmd	Desired	2	1	easy to set pitch picture/very good flying qualities
4	Horiz	H2INI	Desired	5	2	stick force change for a given displacement
5	Horiz	CLASSIC	Desired	-	-	no grade - pilot unsure of workload
6	Horiz	CLASSIC	Desired	3	1	good flying qualities
7	Horiz	MXAOA/H_∞ AOA Cmd	Desired	2	1	best of all 3 flight control systems tested today/negligible deficiencies

Flight #2 **Mission date:** 6 Oct 97 **Winds:** 240/15G25 **Eval Pilot:** Pilot #3 (Cantiello)

Appr	Task	Configuration	Landing Zone	C-H	PIO	Comments
1	St-In	H2AIN	Desired	4	2	trimming continuously/pitch sensitivity in the flare/nose heavy after touchdown
2	St-In	H2AOA	Desired	5	3	hard to trim/very sensitive in pitch/heavy nose after touchdown
3	St-In	MXAOA	Desired	4	3	pitch "bobble" in the flare
4	St-In	H2INI	Desired	2	1	not affected by gusts/very good flying qualities
5	Horiz	H2AIN	Desired	4	2	higher workload due to gusty winds
6	Horiz	H2AOA	Desired	4	3	trimming continuously/pitch sensitivity in the flare/nose heavy after touchdown
7	Horiz	MXAOA	Adequate	5	3	pitch sensitive in the flare/light turbulence
8	Horiz	H2INI	Desired	4	2	mild undesirable motion and pitch sensitivity in the flare/nose heavy after touchdown

Flight #3 **Mission date:** 7 Oct 97 **Eval Pilot:** Pilot #2 (Stevenson)
Winds: 280/18

Appr	Task	Configuration	Landing Zone	C-H	PIO	Comments
1	St-In	MXAOA	Desired	4	2	tendency to overshoot desired pitch attitude
2	St-In	H2AOA	Desired	6	4	small amplitude pilot-in-the-loop oscillation (PIO) in flare/heavy nose on landing
3	St-In	H2AIN	Adequate	5	2	sluggish initial response
4	Horiz	MXAOA	Desired	3	2	predictable/no speed stability feedback/easy to fly
5	Horiz	H2AOA	Desired	4	1	divergent when off trim airspeed
6	Horiz	H2AIN	Desired	4	2	nose pitch up below trim airspeed/higher workload due to constant trim
7	Horiz	H2AOA	Desired	6	4	heavy stick in flare led to PIO/sensitive to pilot bandwidth

Flight #4 **Mission date:** 7 Oct 97 **Eval Pilot:** Pilot #2 (Stevenson)
Winds: 270/20

Appr	Task	Configuration	Landing Zone	C-H	PIO	Comments
1	St-In	CLASSIC	Desired	3	1	predictable and responsive
2	St-In	H2INI	Desired	3	1	predictable/rapid initial pitch response
3	St-In	MXAOA	Desired	3	1	linear response/slight pitch overshoot in the flare
4	Horiz	CLASSIC	Desired	3	1	rapid initial response
5	Horiz	H2INI	Desired	4	2	sensitive to airspeed/high workload to maintain airspeed
6	Horiz	MXAOA	Desired	3	2	small pitch overshoot in flare (turbulence)
7	Horiz	H2INI	Desired	4	3	airspeed pitch sensitivity required higher workload
8	Horiz	MXAOA	Desired	3	1	precise pitch attitude changes required lower gain pilot technique

Flight #5	**Mission date:** 8 Oct 97 **Winds:** Calm	**Eval Pilot:** Pilot #3 (Cantiello)

Appr	Task	Configuration	Landing Zone	C-H	PIO	Comments
1	St-In	CLASSIC	Desired	2	1	beautiful, very good flying qualities
2	St-In	H2INI	Desired	2	1	very good flying qualities/easy to trim
3	St-In	MXAOA	Desired	4	3	more sensitive in the flair/tendency to float
4	St-In	H2AIN	Desired	4	3	pitch sensitive in the flair/had to stay low gain
5	St-In	H2AOA	Desired	3	2	heavy nose in the flare
6	Horiz	H2INI	Desired	3	1	very nice to fly/nice control harmony and response
7	Horiz	CLASSIC	Desired	4	3	moderate workload due to sensitivity in pitch and mild undesirable motion
8	Horiz	MXAOA	Desired	4	3	mild undesirable motion/tendency to float in flare
9	Horiz	H2AIN	Desired	3	2	slightly sensitive in the flare

Flight #6	**Mission date:** 8 Oct 97 **Winds:** Calm	**Eval Pilot:** Pilot #1 (Boe)

Appr	Task	Configuration	Landing Zone	C-H	PIO	Comments
1	St-In	H2AIN	Desired	3	1	no trim problems
2	St-In	H2AOA	Desired	6	3	divergent/worst flown configuration/ heavy stick forces for small speed changes
3	St-In	CLASSIC	Desired	2	1	very good flying qualities
4	St-In	MXAOA	Desired	3	2	pitch "bobble" in flare
5	Horiz	H2AOA	Desired	4	2	hard to trim/heavy nose after touchdown
6	Horiz	H2AIN	Desired	4	2	continuously trimming/heavy nose in flare
7	Horiz	MXAOA	Desired	3	1	no trim problems
8	Horiz	CLASSIC	Desired	-	-	no grade - pilot unsure of workload
9	Horiz	CLASSIC	Desired	3	1	good flying qualities/light turbulence

Flight #7	**Mission date:** 8 Oct 97 **Winds:** 280/5	**Eval Pilot:** Pilot #2 (Stevenson)

Appr	Task	Configuration	Landing Zone	C-H	PIO	Comments
1	St-In	H2INI	Desired	2	1	predictable/no overshoot of pitch attitude
2	St-In	MXAOA	Adequate	-	-	no grade - pilot throttle technique
3	St-In	MXAOA	Desired	3	2	pitch "bobble", one overshoot/predictable
4	St-In	H2INI	Desired	3	1	could the aircraft where the pilot wanted
5	Horiz	MXAOA	Desired	3	2	pitch overshoot eliminated by pilot technique
6	Horiz	H2INI	Desired	-	-	no grade - jet wash
7	Horiz	H2INI	Desired	3	2	airspeed sensitivity, not noticeable in calm winds

Flight #8	**Mission date:** 9 Oct 97 **Winds:** 190/5	**Eval Pilot:** Pilot #1 (Boe)

Appr	Task	Configuration	Landin g Zone	C-H	PIO	Comments
1	St-In	H2INI	Desired	4	2	mild problems in pitch captures/nose heavy after touchdown
2	St-In	MXAOA	Desired	3	1	no trim problems/light stick forces in flare
3	St-In	H2AIN	Desired	4	2	high stick forces when off trimmed condition
4	St-In	H2INI	Desired	4	1	well damped/light turbulence/stick forces change for a given stick displacement
5	St-In	MXAOA	Desired	3	2	undesirable motions during tight control
6	Horiz	H2AIN	Desired	5	1	divergent/stick forces continuously changing for a given stick displacement
7	Horiz	MXAOA	Desired	3	1	very predictable in pitch captures
8	Horiz	H2INI	Desired	4	2	always diverges from trimmed condition/nose heavy after touchdown

Flight #9 **Mission date:** 9 Oct 97 **Eval Pilot:** Pilot #3 (Cantiello)
Winds: 230/10

Appr	Task	Configuration	Landing Zone	C-H	PIO	Comments
1	St-In	H2INI	Desired	2	2	very good fly qualities
2	St-In	MXAOA	Desired	4	1	pitch sensitivity in the flare/ light stick forces/tendency to float
3	St-In	MXAOA	Desired	4	3	undesirable motions which compromised the task
4	St-In	H2AIN	Desired	3	2	hard to trim precisely/small pitch "bobble" in flare
5	Horiz	H2INI	Desired	3	1	good control harmony
6	Horiz	MXAOA	Desired	2	2	no trim problems/easy to fly
7	Horiz	H2AIN	Desired	3	2	slight trim compensation

This page intentionally left blank.

APPENDIX F

DATA RECORDING PARAMETERS

This page intentionally left blank.

DATA RECORDING PARAMETERS

Data parameters recorded during HAVE INFINITY II testing are shown in Table F1.

Table F1
DATA PARAMETER LIST

Item	Parameter
1	α, angle of attack
2	δ_{eact}, actual elevator deflection
3	δ_{evir}, virtual elevator deflection
4	β, side slip
5	θ, pitch angle
6	ϕ, bank angle
7	q, pitch rate
8	p, roll rate
9	r, yaw rate
10	n_z, normal accel
11	n_y, lateral accel
12	n_x, longitudinal accel
13	W_f, fuel weight
14	H, pressure altitude
15	V_c, calibrated A/S
16	Hdot, vertical velocity
17	des, longitudinal stick position
18	fes, longitudinal stick force

This page intentionally left blank.

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Abbreviation	Definition	Units
A/C	aircraft	---
AFB	Air Force Base	---
AFFTC	Air Force Flight Test Center	---
AFIT	Air Force Institute of Technology	---
AGL	above ground level	---
A/S	airspeed	---
ALT	altitude	---
AOA	angle of attack	---
C-H	Cooper-Harper	---
Config	configuration	---
dc	direct current	---
defl	deflection	---
deg	degree(s)	---
des	longitudinal stick position	---
dur	duration	---
FAA	Federal Aviation Administration	---
FBW	fly-by-wire	---
FCS	flight control system	---
fes	longitudinal stick force	---
ft	feet, foot	---
g	acceleration due to gravity	32.2 ft/sec^2
H	pressure altitude	---
Hdot	vertical velocity	---
HQDT	handling qualities during tracking	---

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (Continued)

Abbreviation	Definition	Units
H-Infinity	output energy minimization	---

H2	noise sensitivity minimization	---
ILS	instrument landing system	---
JON	job order number	---
K	thousand(s)	1,000
KIAS	knots indicated airspeed	---
K_a	angle-of-attack gain	---
K_q	pitch rate gain	---
kt	knot(s)	---
MIL-STD	military standard	---
mm	millimeter	---
MSL	mean sea level	---
n_x	longitudinal acceleration	---
n_y	lateral acceleration	---
n_z	normal acceleration	---
pct	percent	---
PIO	pilot-in-the-loop oscillation	---
PTI	programmed test input	---
p	roll rate	---
q	pitch rate	---
RTO	Responsible Test Organization	---
rad/sec	radians per second	---
r	yaw rate	---
s	Laplace transform complex variable	---

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (Concluded)

Abbreviation	Definition	Units
sec	second(s)	---
TPS	Test Pilot School	---
USAF	United States Air Force	---
USN	Unites States Navy	---

W_f	fuel weight	---
VSS	Variable Stability System	---
V_c	calibrated A/S	---
α	angle of attack	deg
β	side slip	deg
δ_{eact}	actual elevator deflection	deg
δ_{evir}	virtual elevator deflection	deg
θ	pitch angle	deg
ϕ	bank angle	deg
ω_n	zero natural frequency	---
ζ	damping ratio	dimensionless

This page intentionally left blank.

DISTRIBUTION LIST

Offsite Distribution	Number of Copies Electronic	Hard Copy
Defense Technical Information Center DTIC/OMI 8725 John J. Kingman Rd., Suite 0944 Ft. Belvoir, VA 22060-6218	0	2
Air Force Institute of Technology/ENY Attn: Dr. Brad Liebst 2950 P Street Wright-Patterson AFB OH 45433	1	3
Flight Dynamics Directorate Attn: Mr. Dave Leggett Wright Laboratory Air Force Materiel Command Wright-Patterson AFB OH 45433-7562	1	3
Flight Research Division Attn: Mr. Russ Easter Calspan Corporation P.O. Box 400 Buffalo, NY 14225	0	1
Onsite Distribution		
USAF TPS/TS 220 S Wolfe Ave Edwards AFB CA 93524-6485	1	0
USAF TPS/EDT 220 S Wolfe Ave Edwards AFB CA 93524-6485	2	6
412 TW/TSTL 305 E Popson Ave., Bldg 1400, Rm 110 Edwards AFB CA 93524-6630	1	1
AFFTC/HO 305 E Popson Ave., Bldg 1406 Edwards AFB CA 93524-6595	0	1
USAF TPS Attn: Captain John R. Anderson 220 S Wolfe Ave. Edwards AFB CA 93524-6485	1	2

DISTRIBUTION LIST (Concluded)

Onsite Distribution	Number of Copies Electronic	Number of Copies Hard Copy
412 TW/TSFF Attn: Mr. Fred Webster 195 E Popson Ave., Bldg 2750 Edwards AFB CA 93524-6841	0	1
412 TW/TSFB Attn: Mr. Bob Lee 195 E Popson Ave., Bldg 2750 Edwards AFB CA 93524-6841	0	1
Total	7	21